FEASIBILITY STUDY
ANTI-TANK MISSILE SYSTEM
USING FIBER OPTIC DATA LINK

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THESIS

FEASIBILITY STUDY
ANTI-TANK MISSILE SYSTEM
USING FIBER OPTIC DATA LINK

by

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Feasibility Study
Anti-Tank Missile System
using Fiber Optic Data Link

by

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LCOL, Canadian Forces
B Eng., Royal Military College of Canada, 1965

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

ABSTRACT

The feasibility of an anti-tank missile system utilizing a fiber optic data link and a CCD camera imaging array is studied. The CCD camera provides a video picture of the target which the operator uses to steer the missile until impact. The optical fiber provides an up and down communication link throughout the engagement period, between the missile and the fire control system. The feasibility of the electronic portions of the missile is verified using current technical literature.

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I. INTRODUCTION

A. HISTORY

Anti-tank systems, capable of destroying a tank, have evolved throughout the last sixty years along with the development of the tank. As the tank became more sophisticated, so did anti-tank systems.

During World War II, most anti-tank weapons were either howitzers or guns that fired shells or guided rockets (American Bazooka and German Panzerfaust). France was the first to develop a guided anti-tank missile called the SS10. Research and Development began in 1950, with operational status being attained in 1956. It was a wireguided missile having a speed of 80 m/sec and a range of 1600 m. Other guided missiles quickly followed, each improving on its predecessor. One of the latest examples is TOW (Tube launched, Optically tracked, Wire guided), an anti-tank missile system developed by the United States during the period 1962 to 1967. Presently (1979) it is operational with eighteen countries. It is supersonic, simple and highly accurate.

To fire TOW at a stationary object or a moving target, the operator simply aligns the crosshairs of his telescopic sight on the target and then launches the missile. The Fire Control System (FCS) in the launcher attempts to make the angle between the missile trajectory and the line of sight of the target, zero (Fig. 1.1). It obtains the location of

the missile by means of a coded IR signal transmitted from the aft end of the missile. Correcting commands are transmitted to the missile by means of the wires.

Figure 1.1 - TOW Aiming System

It is considered one of the best anti-tank missiles in the NATO inventory and through many improvements, it remains one of the best. However, as with any anti-tank system, it does have limitations which affect its probability of a first round hit (being able to hit a target with the first round fired, thus increasing the probability of destroying the target before it is aware that it is being fired upon). Some of these limitations are:

1. TOW requires a direct field of fire. The gunner must have a clear view of the target throughout the engagement time, over the 3 Km range. If some opaque object comes between the gunner and the target, such as haze, the system is blind.

2. The FCS relies on the modulated IR signal to indicate the whereabouts of the missile. From this data, correcting

commands are transmitted to the missile. The countermeasure against the missile is to saturate the IR detector.

3. The probability of detecting the launcher remains very high during the launch phase of the missile.

B. SYSTEM ENGINEERING

The morphology of the design process outlines eight steps in the system engineering approach to equipment design.

- Needs analysis
- Feasibility study
- Preliminary design
- Detailed design
- Production
- Distribution
- Consumption
- Retirement

This paper will carry out the first two steps in the design of an anti-tank missile system. The object is to utilize a new technology, in this case fiber optics, to improve on the capability of a current anti-tank missile such as TOW. In addition, the author became interested in Charge Coupled Device (CCD) imaging systems and their application to anti-tank missiles. This technology, too, has been included to improve the missile's capability.

C. NEEDS ANALYSIS

A new anti-tank missile is needed to combat the sophisticated countermeasures found on the modern battlefield.

Using the TOW missile system as a reference, the need is to improve the probability of hitting the target with the first round fired. A proper needs analysis would consider all engineering aspects of a new missile, such as propulsion, aerodynamics and warhead. This needs analysis, however, due to the size of the team (one), will consider only the electronic engineering aspects.

Figure 1.2 and the following, outline some missile terminology used throughout this paper:

- FCS - major subsystem of launcher which houses the controls for assessing the information obtained from the operator and converting these to flight control commands;
- Down Link - by convention, the link providing information from missile to FCS;
- Up Link - by convention, the link providing information from FCS to missile;
- CCD Camera - area imaging system using CCD technology which provides a composite video output;
- Missile Controls - transducers such as actuator system;
- Video Display - normal video rasterscan display.

Due to the limited scope of this paper, only the following needs were considered:

1. The most important need is to utilize the latest state-of-the-art electronic technology. The lifetime of the system can be increased by using new technology. Two areas of tremendous technical advancement to be considered are:

a. Fiber optics, which has the following advantages over present copper wire systems:

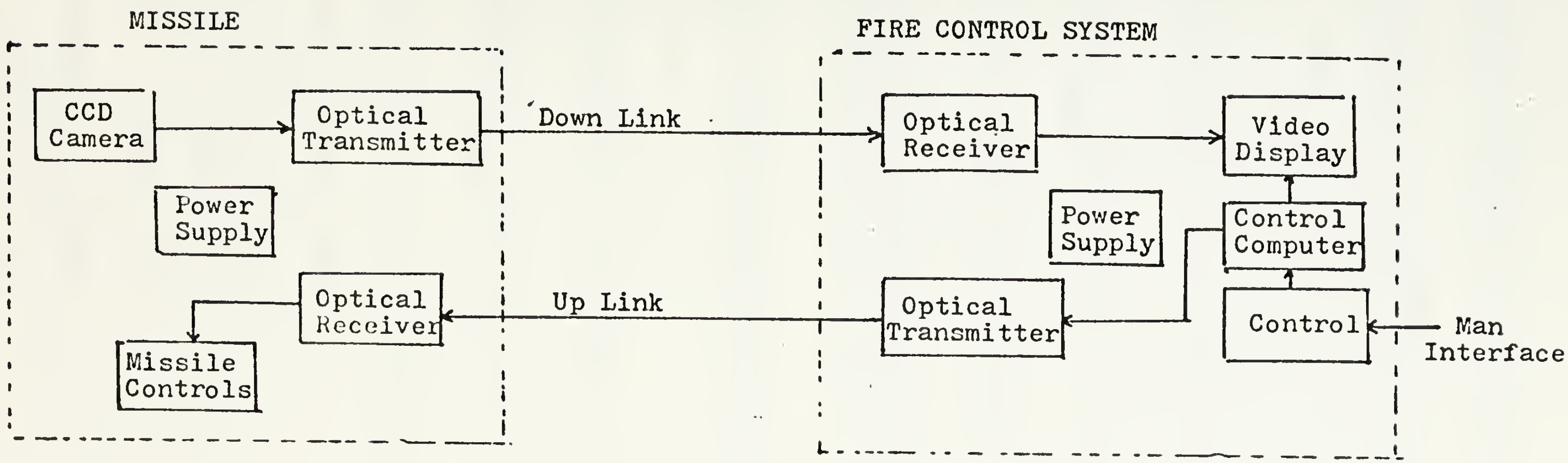


Figure 1.2 - Missile/FCS Block Diagram

- larger bandwidth to provide more information to the FCS such as a video picture;
- RFI/EMI/noise immunity for utilization in an electronic warfare environment;
- no spark/fire hazard for use around high explosives;
- no short circuit hazard for higher reliability;
- compatibility with solid state devices which provide higher reliability;
- possible cost savings as fibers become cheaper than copper wire; and
- no cross talk which simplifies placing up and down links in the same enclosure.

b. Charge Coupled Device Area Image Sensor Arrays, which, in adding a video capability to the missile, have the following advantages over electron beam scanned camera tubes:

- use of solid state devices which are smaller and weigh less for use in a missile;
- consume less power;
- more rugged to withstand the high G force of launch and high vibration force during the flight;
- compatible with other solid state devices and therefore more reliable;
- better immunity to electromagnetic fields for utilization in an electronic warfare environment;
- provide better SNR.

2. To increase the probability of survival for the operator, the system must be completely passive. The target must receive no warning that it is under attack until impact, thus increasing the probability of first round kill.

3. The target must not have a direct field of fire to the operator. The operator must be able to acquire, track and attack a tank while remaining hidden from view from

the enemy. Figure 1.3 indicates the four phases of the missile's flight. The phases are as follows:

- Launch Phase

  Position A -Missile indirectly fired from same location as operator when target's general whereabouts is known;

  Position B -Missile fired from this position when target must be acquired prior to launch;

- Acquisition Phase

  -Period during which the operator locates and identifies the target. If missile is launched from position B, acquisition phase is completed prior to launch;

- Track Phase

  -Operator continues to correct flight path due to movement of target. A more complex FCS might assist him to maintain a constant cruise altitude;

- Terminal Phase

  -Operator steers missile until impact.

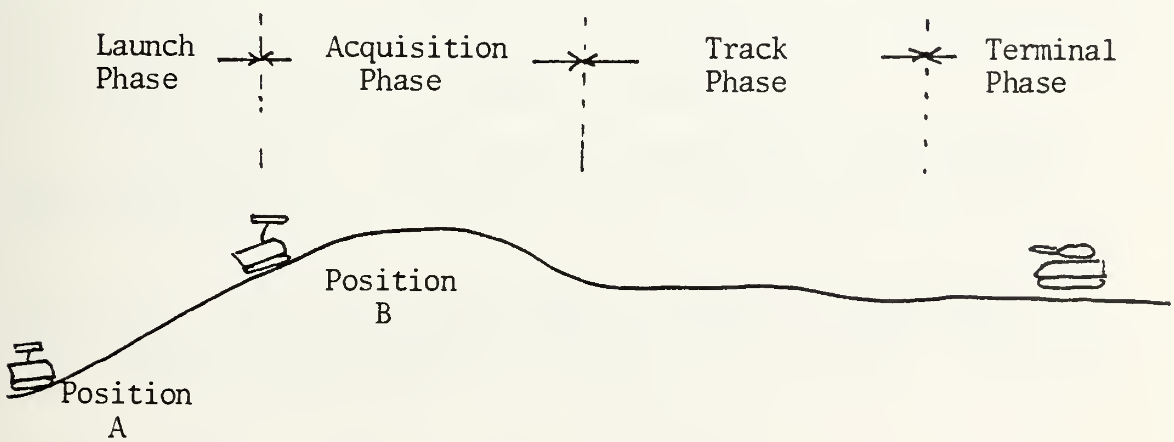


Figure 1.3 - Missile Flight Phases

4. Cost of individual missile must be minimized by designing the more expensive electronic components into the launcher. The components designed into the missile must have maximum shelf life. The missile system must be self-contained, having its own power supply;

5. The range of this missile must be 5 Km minimum. This gives it an added advantage over its primary target, the tank, which has a main armament range of approximately 3 Km;

6. The system must take into account all present and planned electronic warfare countermeasures;

7. Update capabilities must be considered for all components.

The culmination of a needs analysis is a specification. The specification outlines the minimum operational requirements for the system. The specifications of the desired system are:

- Type: surface to surface guided weapon for anti-tank role;
- Guidance Principle: command to impact;
- Guidance Method: video target tracking; fiber optic guidance control of missile's gas-operated aerodynamic tail surfaces;
- Mobility: overall system must be adaptable to military vehicles which now carry TOW or DRAGON. Individual missiles in their sealed storage and transport container must be man portable;
- Speed: must be greater than 150 m/sec;
- Range: at least 5 Km;
- Target Acquisition: passive;
- The specifications of the mechanical portions of the missile have not been considered except where they affect the electronic portions.

D. RESTRICTIONS

Much of the work presently (1979) being done in this area by the U.S. Army is classified. Engineering trials are being conducted by the Army's MIRADCOM in Alabama and initial contracts for engineering trials on subsystems have been given to ITT and Hughes Aircraft Company. However, for ease of administrative control, the author chose to write an unclassified thesis. This does restrict the scope of the thesis as any mention of the above work must be on the unclassified portions only. Nevertheless, there is still sufficient material available to carry out a feasibility study of an anti-tank missile system.

II. NATURE OF FEASIBILITY STUDY

The aim of any feasibility study is to show that the original need, as outlined in the needs analysis, can be satisfied with current technology. During the study, a product first begins to appear in abstract form. A solution is proposed and studied to determine whether in fact it has a feasible existence. Alternate solutions may or may not be proposed, as dictated by the application, to ensure all possibilities have been considered. A feasibility study is an ongoing task throughout the design process until production. It ensures nothing has been forgotten which could jeopardize the performance of the final product.

The following study will look at the feasibility of the author's proposed anti-tank missile system. The study will restrict itself to the nonmechanical portions of the system. This section will outline the scope of the study and will discuss the basics of the two technical areas of interest, CCD Imaging Systems and Fiber Optics.

A. SCOPE

To design a complete anti-tank system of the complexity and magnitude envisaged in the needs analysis requires a team of engineers covering many fields. The team would consist of specialists for each field plus a system engineering section. The system engineering section would be responsible for the overall coordination of the team.

Although this paper does not deal with system engineering specifically, the ideas of this field must be an integral part of any design process. References 1 and 12 were consulted to ensure a systematic approach was used to derive a coherent system. The main features of system engineering have been included as Appendix E to emphasise their importance in this study.

The scope of this paper will limit itself to two areas of interest. The first area is the Fiber Optic Data Link (FODL) between the missile and the launcher. The second area of interest is the camera mounted in the nose of the missile which provides a video picture to the operator over the FODL. The aim is to look at applying current technical knowledge in these two areas to an anti-tank missile system.

B. CCD IMAGING SYSTEM

The first area of interest is the imaging system placed in the nose of the missile. As indicated in the needs analysis, we are looking for a solid state ruggedized system capable of a high G force on launch. We have chosen the CCD camera as the solution to our problem. Before discussing an actual system, this paper will review how the CCD works as well as how an area imaging sensor functions. Emphasis will be placed on those topics that relate to a missile. Reference 2 is an excellent source of information.

1. Basic CCD

Charge Transfer Device (CTD) is a generic term which has come to be applied to a family of functional solid-state electronic devices which include bucket-brigade devices (BBD) and charge coupled devices (CCD). Appendix A contains a glossary of solid state imaging terms. Under the application of a proper sequence of clock pulses, these devices move quantities of electrical charges in a controlled manner across a semiconductor substrate.

In 1970, CCDs were introduced as integrated circuits which needed only a single level of metal and no diffusions. The initial work was done by Boyle and Smith at the Bell Laboratory. They first proposed a structure using uniform electrodes and a 3-phase clocking system as the minimum required to isolate individual charge packets. Within two years, Kahng and Nicolliam, also of Bell Labs, recognized that structures which need only two driving phases could be designed by introducing asymmetry into each electrode. By 1973, a 13000 element CCD was demonstrated as an image sensor for low resolution television.

The basis of the CCD is the metal-oxide-silicon (MOS) capacitor. A potential well is formed by applying a positive voltage to the metal electrode, thus repelling the majority carriers. It is customary to think of the potential well as a bucket and of the minority charge as a fluid that partially fills this container.

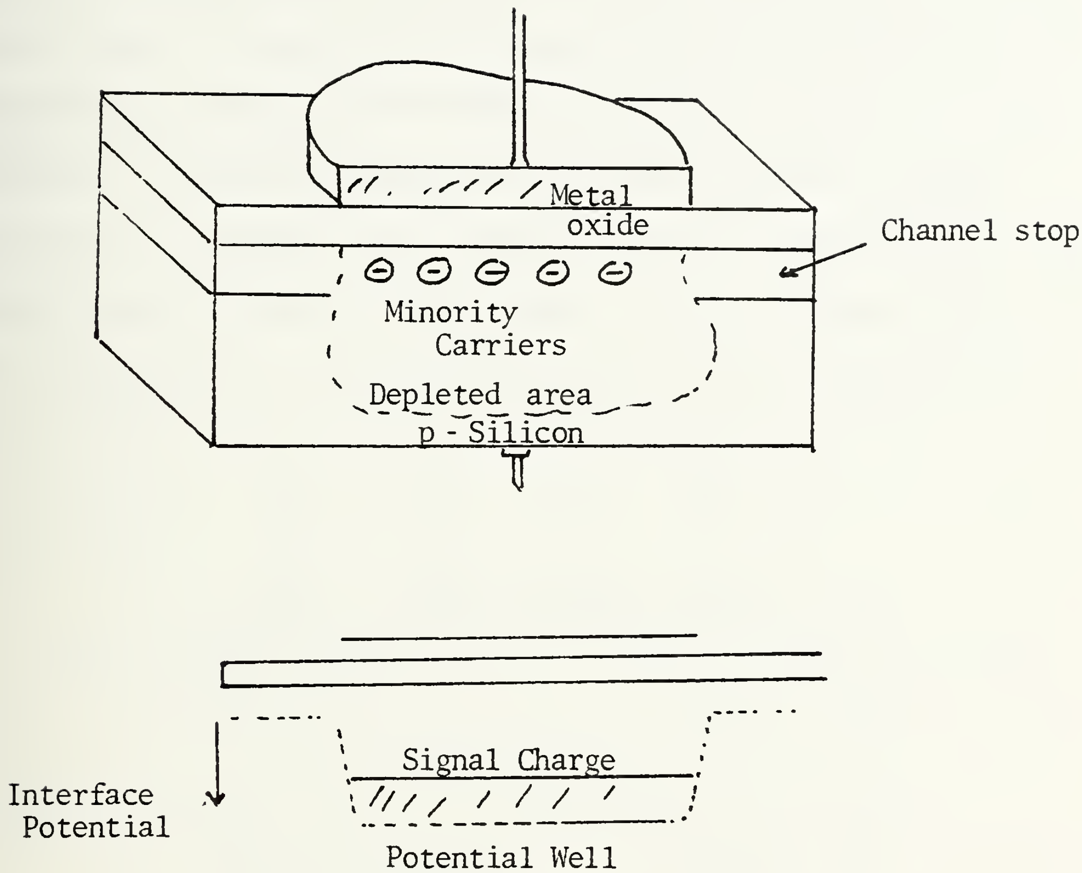


Figure 2.1 - Cross Sectional View of MOS Capacitor

If two MOS capacitors are placed so closely together that their depletion regions overlap and their potential wells merge or "couple," mobile minority charge will accumulate at the location with the highest interface potential. Charge flows to the deepest part of the combined potential well. This gives the possibility of transferring charge in

a controlled manner from one electrode to an adjacent one. If, for instance, a charge packet has been generated optically under one electrode which is at a high potential, it will spread along the silicon-silicon dioxide interface when the neighboring electrode is turned on to the same or a higher potential. When the potential on the original storage electrode is reduced, the charge packet is completely transferred into the new location (Fig. 2.2). Devices using this mode of operation are called Surface Channel CCDs (SCCD).

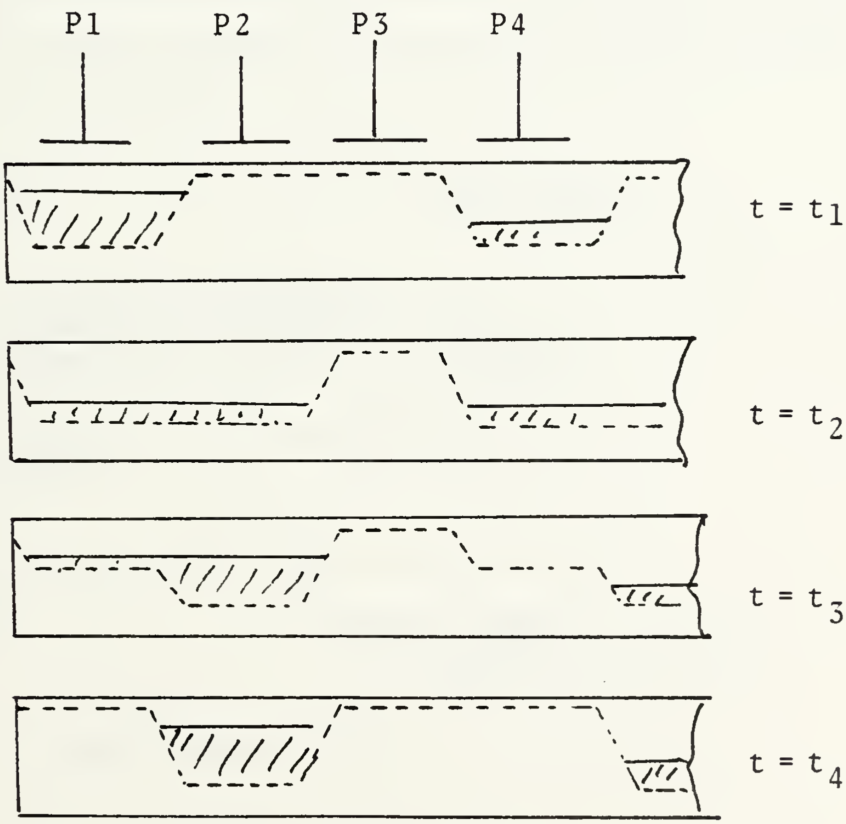


Figure 2.2 - Movement of Potential Wells - 4 phase

A device which transfers charge faster and more efficiently than the SCCD is the bulk channel CCD (BCCD). It involves the use of an epitaxial or ion implanted silicon layer of opposite polarity to that of the substrate. This shifts the maximum potential of the wells away from the interface and into the bulk. Such a layer is shown in Fig. 2.3. It is in electrical contact with the input and output diodes of the CCD which drain out all mobile carriers under a suitable reverse bias. The clock pulses applied to the transfer electrodes modulate the channel potential to produce moving potential wells which can store or transfer charge packets like in the SCCD.

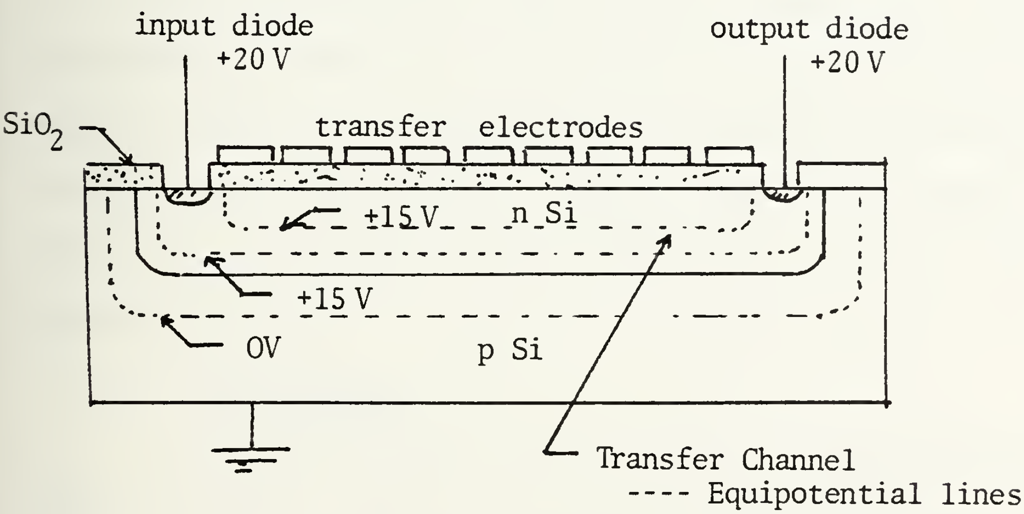


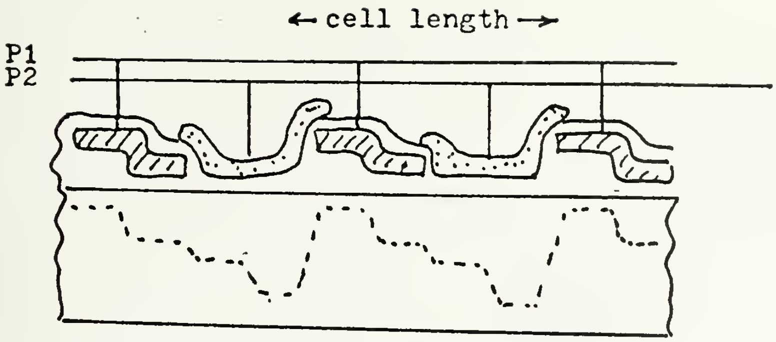
Figure 2.3 - Bulk Channel CCD

Innumerable different electrode structures have been proposed, and many have been successfully implemented in the laboratory. But only a few are finding extensive application. In general, there is a tradeoff between performance, ease of fabrication and cell size. The configurations are grouped according to the number of independent electrodes that constitute one unit cell. Figure 2.4 shows some examples. There are many other two, three and four phase configurations. The choice depends on the basic physical limitation of each and their relation to the demands of a particular application.

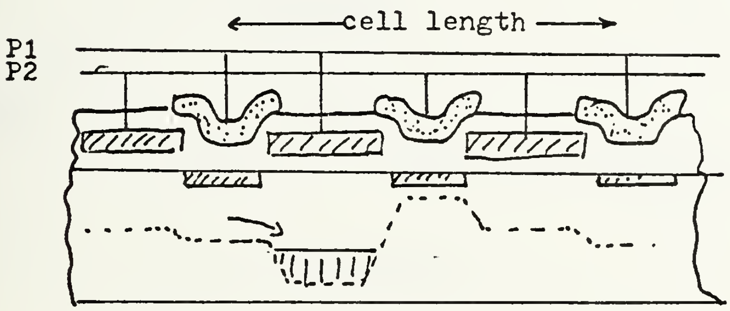
There is also a need for lateral confinement too. A transfer channel has to be defined in order to keep the minority carriers confined in the lateral direction. Not only must the potential well be limited but the edges of the channel should be held in accumulation to prevent additional charges leaking into the channel. This is done by a channel stopping diffusion or implant, by an oxide step, or by a special field shield electrode.

2. CCD Imaging

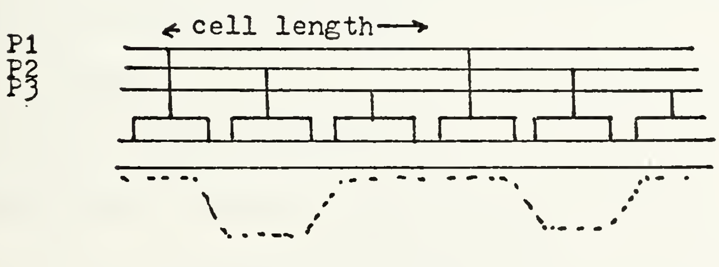
The CCD has an "electro-optic" property which means that it absorbs radiation in the silicon substrate and generates electrons in a quantity directly proportional to the amount of incident radiation. Conceptially, the CCD is an analog shift register designed in such a way as to accept and transport information samples in the form of individual charge packets. As seen by Fig. 2.5, these packets result from visible and near IR radiation.



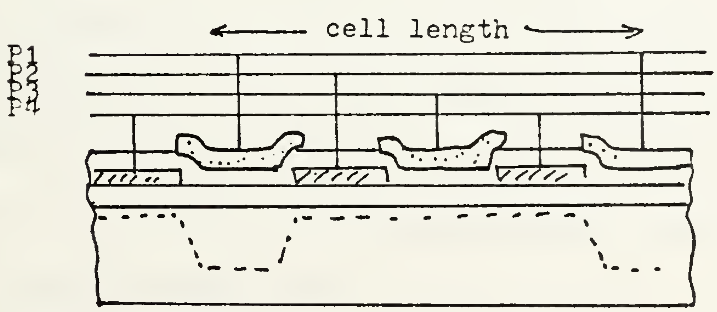
(a) 2 phase CCD (implanted barrier)



(b) Standard 2 phase CCD



(c) 3 phase CCD



(d) 4 phase CCD

Figure 2.4 - CCD Configurations

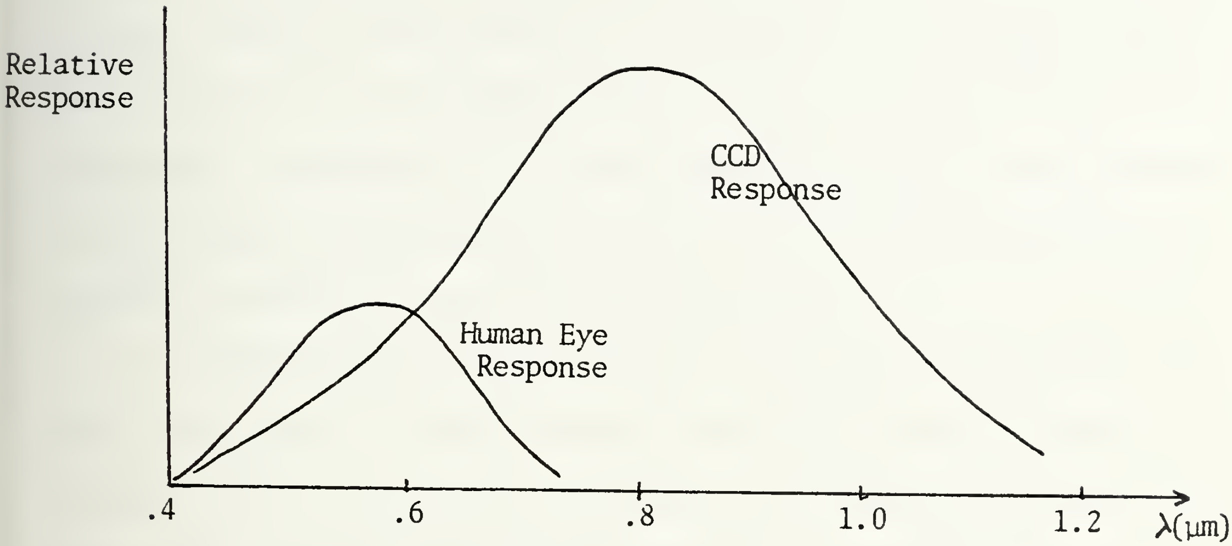


Figure 2.5 - Relative Responses

There are three mechanisms that can place charge into the potential wells of a CCD:

- dark current
- electrical charge injection
- photoelectric carrier generation.

Dark current is an unwanted signal that we try to prevent. Electrical charge injection is used in signal processing and memories, subjects of no concern to this thesis. Charge generation by photons is the major function of image sensors. For an output, the CCD has the advantage that all charge packets can be detected at a single small output diode. Increased signal to noise ratio is the result. The BCCD, particularly when cooled, will give superior performance over the SCCD. Its charge transfer efficiency is high for the

full range of electron packet size, from a saturation charge of approximately 10^6 electrons to 10 electrons or less. Wide dynamic range is obtained by a straightforward design whereas with the SCCD, it is necessary to cope with the level of the invariably required "fat zero" channel current (see Appendix A), the means of introducing the "fat zero" and the noise sources related to the "fat zero" current.

Solid state image sensors can readily be subdivided into two groups: linear image sensors and area image sensors. Linear sensors consist of a single row of photosensitive elements and can thus be used to monitor a one-dimensional variable. For closed circuit television, it is necessary to use an area sensor.

Listed in Table II.1 are some of the design issues and options for CCD Area Imagers.

Issue	Options
Organization	Frame transfer, interline transfer, line transfer
Illumination side	Front, back
Channel mode	Surface, buried
Anti-blooming control	None, element-type, column-type
On-chip preamplifier	None, GCI, FGA, DFGA
Clocking	2-Phase implanted barrier, 2-phase stepped oxide, 3-phase, 4-phase

Table II.1 - CCD Area Imager design issues and options

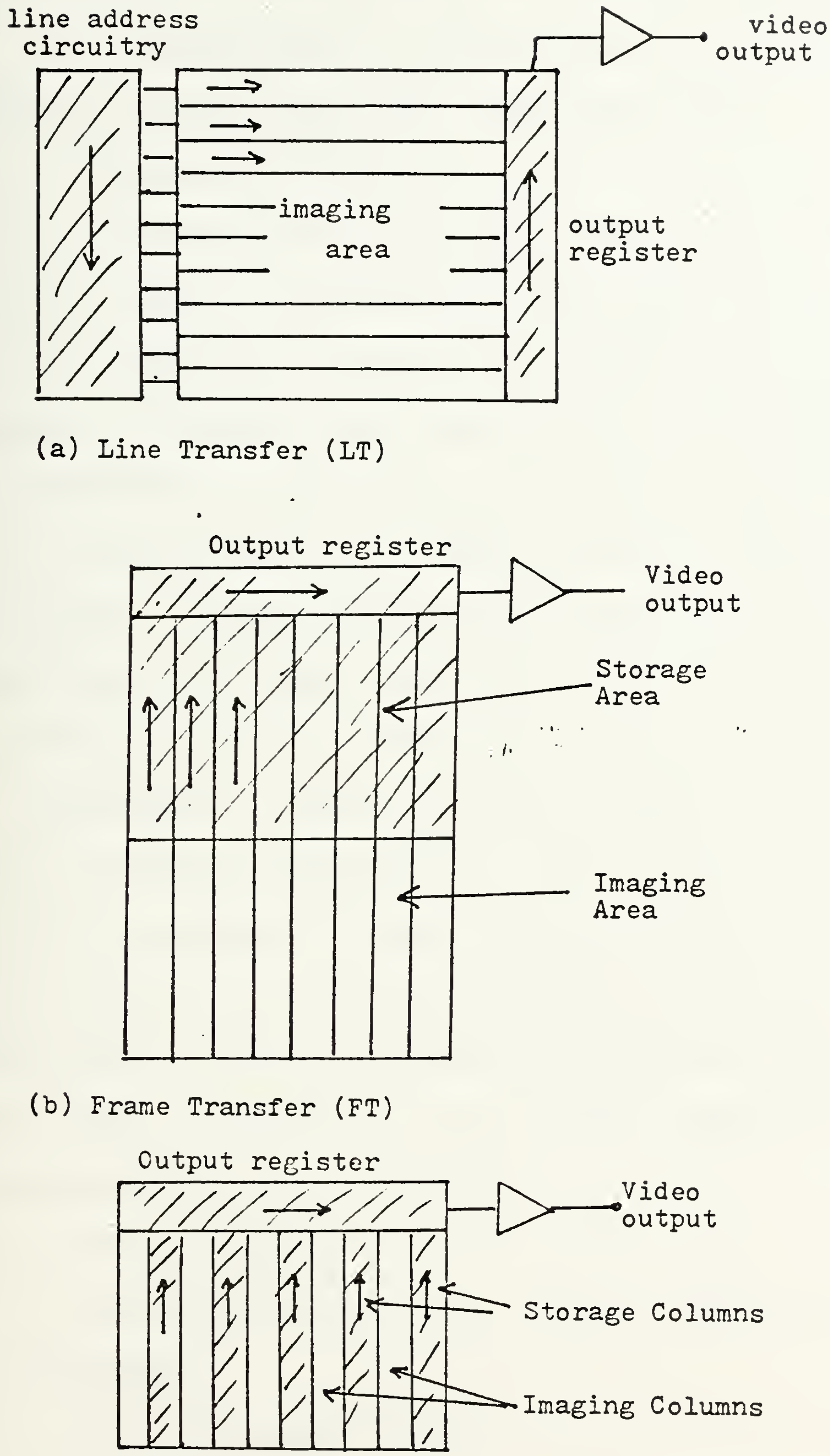
a. Organization

The main goal of any organization is that all charge packets should be shifted to a single small output diode. Also, the readout sequence from the device normally has to match the format of a line scanned television display. Furthermore, the organization has to minimize optical smearing which results if the integrated charge pattern is moved across illuminated regions of the array.

The first organization [1970] was the Line Transfer (LT) type (Fig. 2.6a). A complication in this device arose because the readout of each line had to be started with proper timing to compensate for the variable amount of delay experienced in the vertical readout register.

The second method, Frame Transfer (FT) (Fig. 2.6b) is simple and has a good SNR. Its disadvantage is the need for additional storage area. The first solid state area image sensor which reproduced a human face with reasonable resolution was an FT type [1973].

To avoid optical smearing in horizontal line readout or vertical frame transfer, the designers turned to the Interline Transfer (ILT) organization (Fig. 2.6c). Imaging and storage functions were integrated within the same area and the frame or field transfer took place in a single step. Charge is accumulated in the separate integration sites, while the previous field is shifted along the vertical channels by one element during each horizontal retrace period. Each site can be read out on alternate fields, thus providing



(a) Line Transfer (LT)

(b) Frame Transfer (FT)

(c) Interline Transfer (ILT)

Figure 2.6 - Types of Organization for CCD Area Image Sensor

the integrated information ready for display in an interlaced format. The disadvantage of this structure is that it is more complex and has less light sensitive area.

b. Illumination Side

Illuminating solid-state image sensors from the backside can improve quantum efficiency and avoid the fluctuations in the spectral response that come with frontside illumination. However, image smearing can result by photoelectron diffusion in going from the backside point of generation to a potential well. Where infrared responsivity is not of concern, backside illumination through an extremely thin substrate is optimum; relatively high modulation transfer function (MTF) and quantum efficiency can be obtained at all visible wavelengths. However, where infrared responsivity is desired, thicker substrates are required and a substantial loss of MTF is incurred for most of the visible spectrum. In frontside illumination, a thicker substrate does not degrade the visible spectrum MTF, although the quantum efficiency is in general less. Basically, the cost and complexity of backside illumination is not justified.

c. Channel Mode

This has already been resolved and most area sensors are BCCDs.

d. Anti-blooming Control

Image blooming in a camera is an undesirable phenomenon. It is an apparent increase in the size of an image of a bright object under overload conditions.

Excess carriers from a localized overload can diffuse through the bulk to neighboring wells causing a circular spreading of a white area in the display. In addition, in CCDs, the charge can spread along the transfer channels producing white streaks in the display.

To avoid this propagation of excess charge, the silicon surface underneath the non-integrating electrodes can be biased into accumulation. This forces excess carriers to be spilled into the substrate, thus reducing the amount of blooming. Complete blooming suppression can be obtained by placing special overflow drains, in the form of reverse biased diodes, between the integration sites. They drain off excess charge.

Most sensors on the market today incorporate only one anti-blooming charge sink per sensor column. A device with this feature can bloom within columns, but not between columns. This is a compromise between effectiveness and complexity/cost.

e. On-chip Preamplifier

As noted in Table II.1, there are a number of possibilities for on-chip preamplifiers. The most common one is the Distributed Floating Gate Amplifier (DFGA). The concept of operation is based on the property of CCDs that signal charge can be passed under a sensing electrode and then further transported to other sensing electrodes with no signal degradation. By sensing the signal charge repeatedly, it is possible to improve the SNR in power, relative

to a single stage amplifier, by the number of times the signal is sensed. By summing the amplified signal in a second CCD register, proper reconstruction of the signal in the time domain is automatically obtained.

Figure 2.7 is a basic schematic of a DFGA. A four phase register clocking scheme is used to obtain maximum flexibility, the input and output registers are driven by the same set of clocks. There is no clearly defined optimum to the number of stages. Since the fundamental principle behind the DFGA concept shows that the SNR in voltage improves as the square root of the number of stages and since the size of each stage of the output register must be increased linearly as the number of stages increases, SNR increases as the one-fourth power of the output register area.

f. Clocking

Most present day sensors use two-phase clocking which is simple but effective.

A data sheet for a typical CCD is attached as Appendix B. This is for the Fairchild CCD 211, 244 x 190 element area image sensor. It is included because it is the basis of the Fairchild MV 201/202 Camera, the imaging system considered in this feasibility study. Additional information on its performance is available in references 6, 7 and 8.

C. FIBER OPTICS

The other area of interest in the study of an anti-tank missile system is the fiber optic data link (FODL).

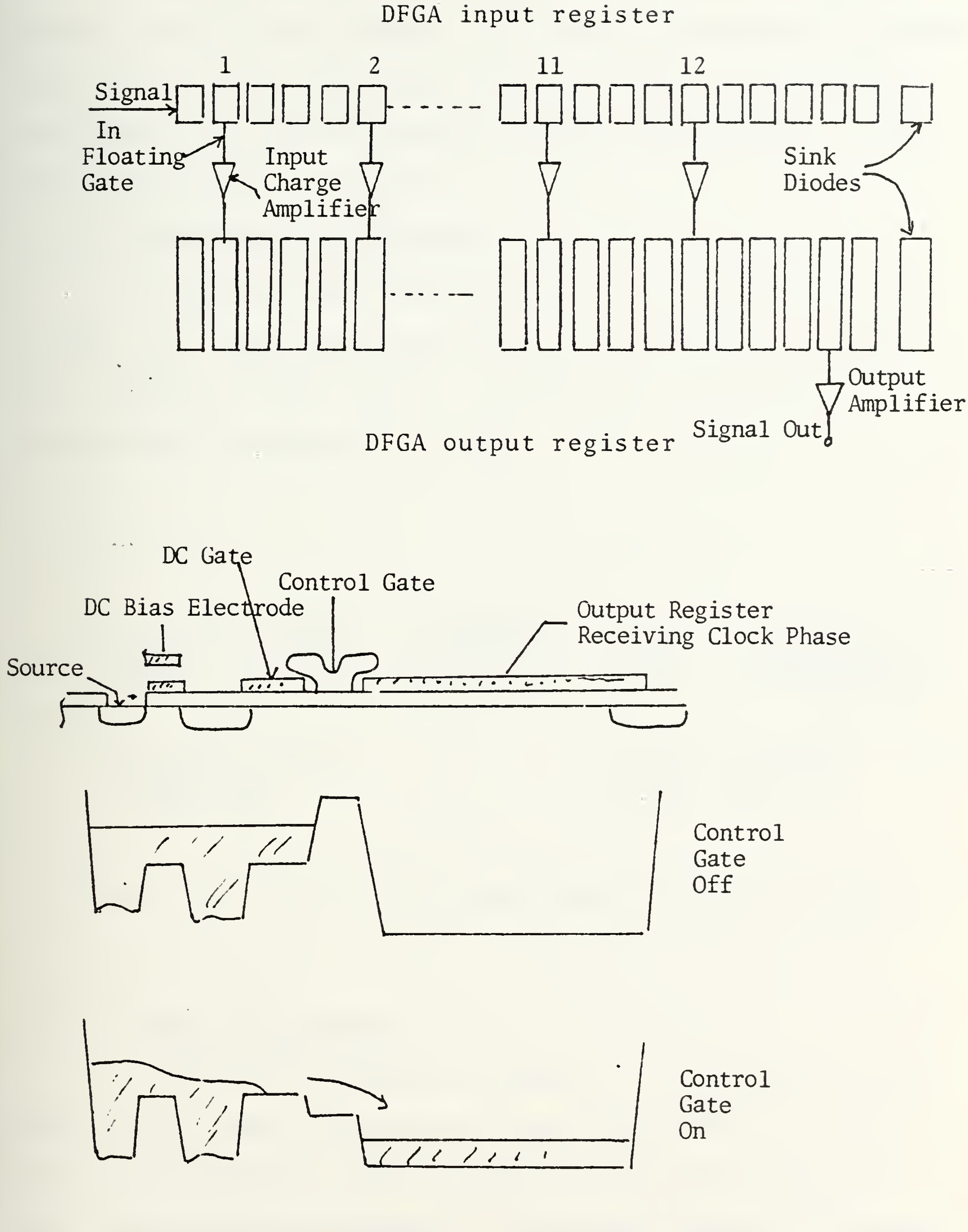


Figure 2.7 - Distributed Floating Gate Amplifier

Previous missiles have used copper wire for the data link between missile and launcher. The limited bandwidth of copper wire restricts the amount of information that can be passed. The copper wire cannot pass the desired video signal. Only fiber offers this capability.

1. <u>Fundamentals of Fibers</u>

The basic fiber optic communication system is shown in Fig. 2.8. The components shown will provide an outline for a review of fiber optics. Additional detail may be obtained from references 9 and 10.

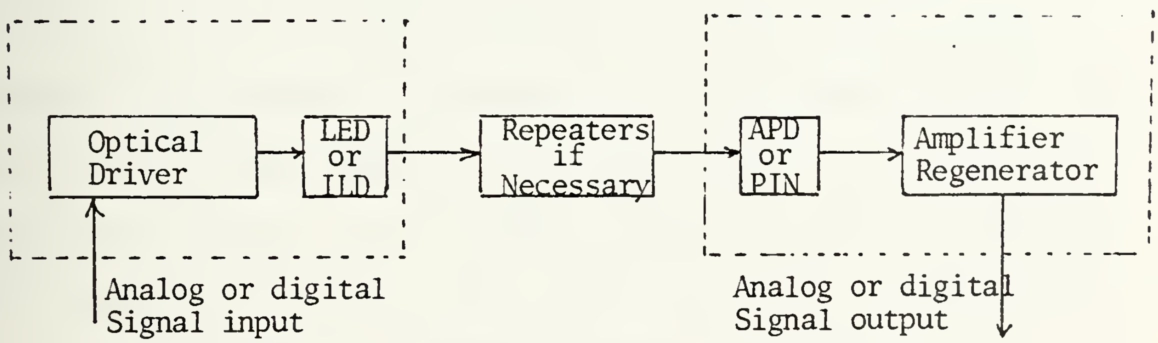


Figure 2.8 - Basic Fiber Optic Communication System

2. <u>Fibers and Cables</u>

A fiber is an optical waveguide. A necessary condition for the fiber to propagate the light signal is total internal reflection. Total internal reflection can only occur when light is incident on a boundary where it is passing from one material to another that has a lower index of refraction. See Appendix C for a glossary of fiber optic terms.

Fibers may be separated into two classes by their modal properties; single mode or multimode. The multimode fiber type includes both step and graded index profiles and usually contains many hundreds of modes. Single mode propagation is realized by designing core sizes to be a few wavelengths in cross sectional dimension and by having small differences in index of refraction.

Loss of optical power in the fiber is generally attributed to absorption and scattering. This combination is designated as attenuation (dB/Km). As shown in Fig. 2.9, attenuation is a function of wavelength. Multimode fibers are relatively insensitive to small changes of wavelength because the presence of hundreds of modes leads to an averaging of losses from higher order modes over all wavelengths. Single mode fibers are extremely selective and are designed for a wavelength of interest. More interest is being directed towards the single mode fiber because it is relatively insensitive to microbending losses. Single mode fibers potentially offer the lowest loss and highest bandwidth for optical data transmission. For more detail about losses such as transmission and coupling losses, refer to references 9, 10 and 11.

Dispersion is another figure of merit used when discussing fibers. The two types of dispersion are multimode group delay spreading and material dispersion, both of which limit the data rate capacity. Light which enters a fiber at an angle other than along the central axis takes longer to transverse the length of the fiber. The difference in total

distance traveled by central axis and off-axis rays causes a time lag to occur which broadens the input pulse. To minimize pulse dispersion due to group delay distortion in multimode fibers, the differential in the index of refraction of the core and cladding is made less than 0.007. This, however, makes the coupling of the input light source very difficult. In single mode fibers, material dispersion is the dominant one. To minimize pulse dispersion due to material dispersion, it is recommended that graded index fiber with a parabolic index profile be used.

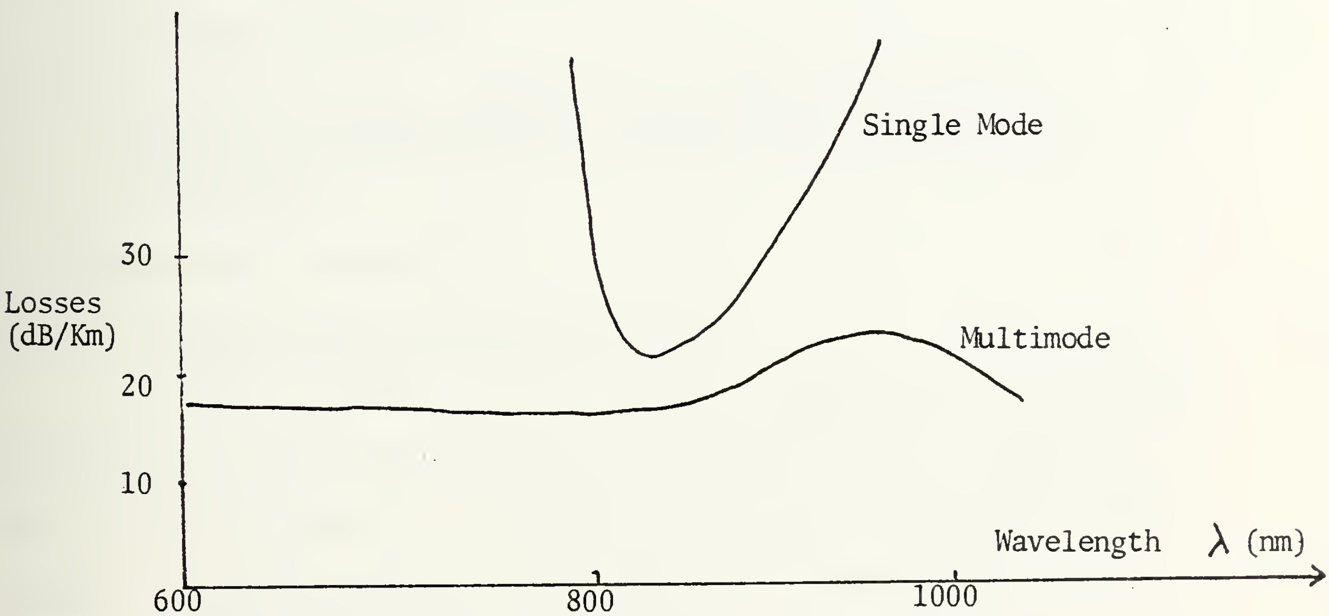


Figure 2.9 - Attenuation as Function of Wavelength

In general, the system engineer does not concern himself with how the fiber is fabricated or what material is used. He evaluates the fiber by using the following fiber parameters:

- reflection coefficient - ratio of forward-to-reverse power along transmission line at a given location;

- signal level - peak and average carrier power contained within the waveguide;

- losses - transmission
  - coupling
  - component

- pulse spreading

- signal to noise ratio

- impulse noise

- temperature resistance - usually rated by maximum and minimum and variations of transmission attenuation as a function of temperature

- corrosion resistance

- stress resistance - ability to withstand tensile torsion and compressive stresses under dynamic and static conditions and resistance to impacts and vibrations

- radiation resistance

3. Light Sources and Modulators

Light sources for fiber optic communication systems require certain characteristics including long lifetime-in use, high efficiency, reasonably low cost, sufficient power output, capability for various types of modulation and physical compatibility with fiber ends. The two light sources that meet these requirements are:

- Light Emitting Diodes (LED)
- Injection Laser Diodes (ILD)

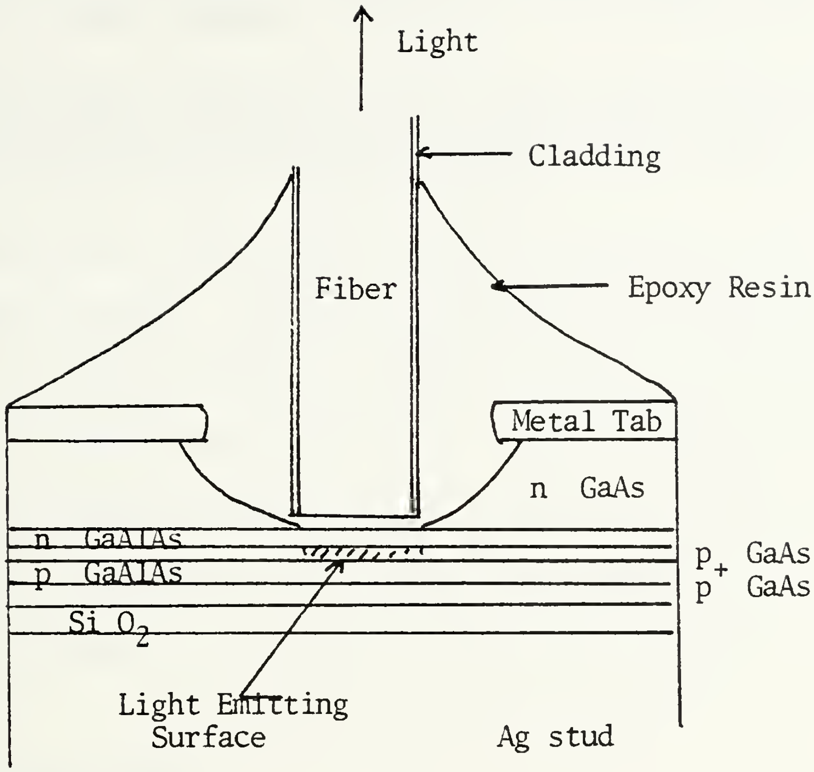
The most commonly used semiconductor material is GaAlAs. Appropriate doping and construction variations can extend the emission wavelength range from 0.75 to 1.06 um and the

expected life-time to 5 x 10^4 hours. Lasers can launch more power into low N.A. fibers than LEDs. The power output from ILDs, however, is more temperature sensitive than LEDs. This temperature dependence requires a special feedback or electronic drive circuit, thus adding to the cost of ILDs. By 1981, it is estimated that LEDs should cost about $6.00 each and ILDs about $25.00 each. It is also expected that sources at 1.3 um will be more readily available than they are today, although at a higher cost than conventional sources. Figure 2.10 shows the construction of a LED and ILD.

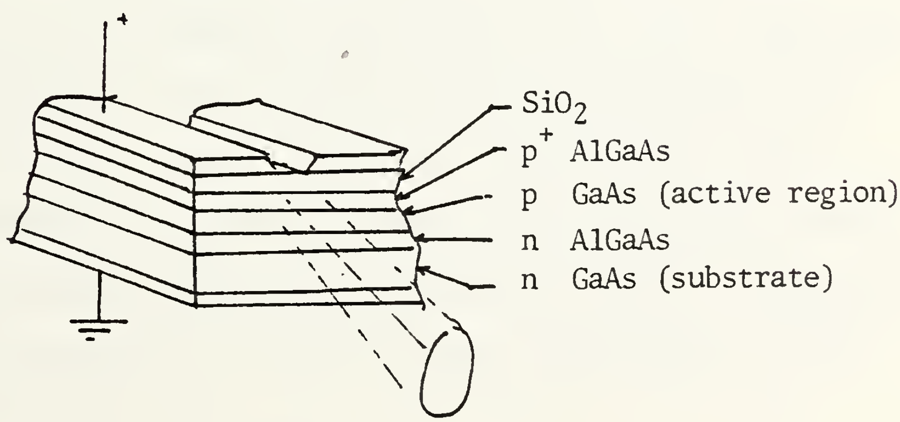
References 9 and 11 have tables comparing some of the LEDs and ILDs on the market. In general, LEDs are best suited for analog applications because light output is nearly a linear function of drive current. Edge or side emitting diodes versus surface LEDs produce a narrower beam source with significantly reduced N.A. losses. ILDs are exceptionally well suited for use in digital fiber optic systems. They have a rise time of less than 1 nsec. Their spectral linewidth is so small (2 to 4 nm) that material dispersion in fibers becomes negligible.

Light sources can be modulated by externally modifying the emitted light after it leaves the source or by directly affecting the source, usually by current variations. The typical method of modulation of LEDs and ILDs is by directly modulating the input current by:

a. direct modulation which has an intrinsic time delay associated with the rise-time to get above the threshold current;



(a) High Radiance Burrus type LED



(b) Injection Laser Diode

Figure 2.10 - Light Sources for Fiber Systems

b. biasing just below threshold and modulate the desired signal to levels above threshold (eliminates time delay but adds constant threshold level noise to output);

c. biasing above threshold (eliminates time delay but adds threshold noise and continual (background) noise to photodetector and decreases expected life-time by requiring higher total energy output).

Light source encoding is widely used to produce a more efficient system. Digital transmission using time division multiplexing (TDM) is presently being introduced because it is less expensive than frequency division multiplexing. For analog transmissions there are various methods of modulation. Intensity Modulation (IM) seems to be the most popular because it is most compatible with existing light sources.

4. <u>Photodetectors</u>

Photodetectors, which convert incident light into electrical energy, must meet numerous physical and electrical requirements. For instance, they can add only a minimal amount of noise to the signal, must have sufficient bandwidth (speed of response) to track light intensity variations in the transmitted light, must have peak sensitivity at the light source wavelength, must be stable over changing external temperatures and must give long life-time in use at reasonable cost. The two detectors that meet these requirements are:

- PIN Photodetectors
- Avalanche Photodiodes (APD)

Photodiodes are usually rated by four parameters: response time, quantum efficiency, total noise equivalent

power and responsivity. Reference 9 has tables comparing some of the PINs and APDs on the market. APDs are used in applications requiring greater sensitivity because they have greater response speed and multiplication or gain characteristics. As shown in Fig. 2.11, properly designed APD receivers can add more than 15 dB extra sensitivity compared with PIN receivers. Also shown is the Quantum Limit in detection. This is the ultimate in sensitivity, the minimum detectable signal with no dark current. Because of its internal gain characteristics, the APD's sensitivity is very close to the Quantum Limit. However, an APD costs $150 to $250 compared to $10 to $50 for a PIN. APD devices must operate at higher voltages and require a greater degree of control on current and voltage.

Since repeaters will not be used in the FODL, they will not be discussed here.

5. <u>Connectors, Couplers and Splices</u>

Connectors that couple cables to terminal equipment must provide low-loss, quick, permanent connections which are small and rugged. In the case of the FODL, connectors are important for the attenuation they add to the overall transmission line circuit. Single fiber connectors, although more difficult to use than bundle connectors, have total coupling losses as low as 0.5 dB.

Again, since couplers and splices will not be part of the FODL, they will not be discussed.

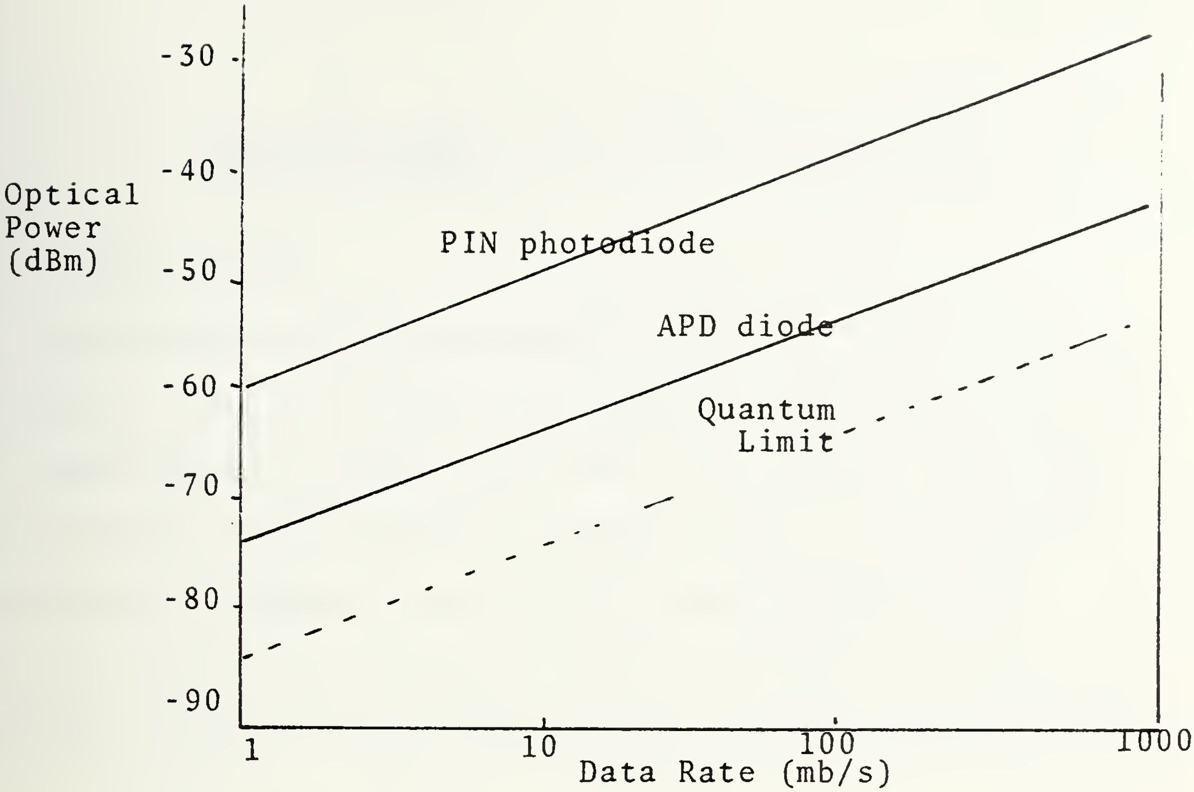


Figure 2.11 - Comparison of APD and PIN Receiver Performance

D. OPTICS

The missile system has a requirement for two sets of lenses, a fixed focus lens on the missile and a zoom lens on the launcher.

The fixed focus lens is used in conjunction with the CCD camera to provide a video picture for transmission over the FODL. The zoom lens on the launcher is used by the operator to first locate and identify the target and then to keep track of the missile in relation to the target. It is sufficient to know that lenses do exist for use on a missile system. They were field tested in Vietnam.

III. DATA FOR FEASIBILITY STUDY OF ANTI-TANK MISSILE SYSTEM

A. OVERALL SYSTEM

The proposed anti-tank missile system consists of two subsystems, the missile and the launcher. The two subsystems are connected by a fiber optic data link (FODL). The basic block diagram of the system is shown in Fig. 3.1. The two main areas of interest are the CCD camera subsubsystem located in the missile and the fiber optic data link located partially in the missile and partially in the launcher (FCS).

B. MISSILE SUBSYSTEM

Figure 3.2 is a block diagram of the missile. It consists of the following:

1. Lens - section III.C;
2. CCD and Sensor Unit - section III.D;
3. Fiber Optic Data Link - section III.E;
4. Electronic Control Unit - section III.F;
5. Warhead - no further discussion;
6. Boost/Sustain Motor - no further discussion;
7. Miscellaneous Mechanical Devices - no further discussion (actuators, gyros, wings, etc.).

The missile is restricted in size in that it must be compatible with the present inventory of tracked military vehicles. Using the TOW missile as a reference, the overall weight of the missile in its launch container should be less

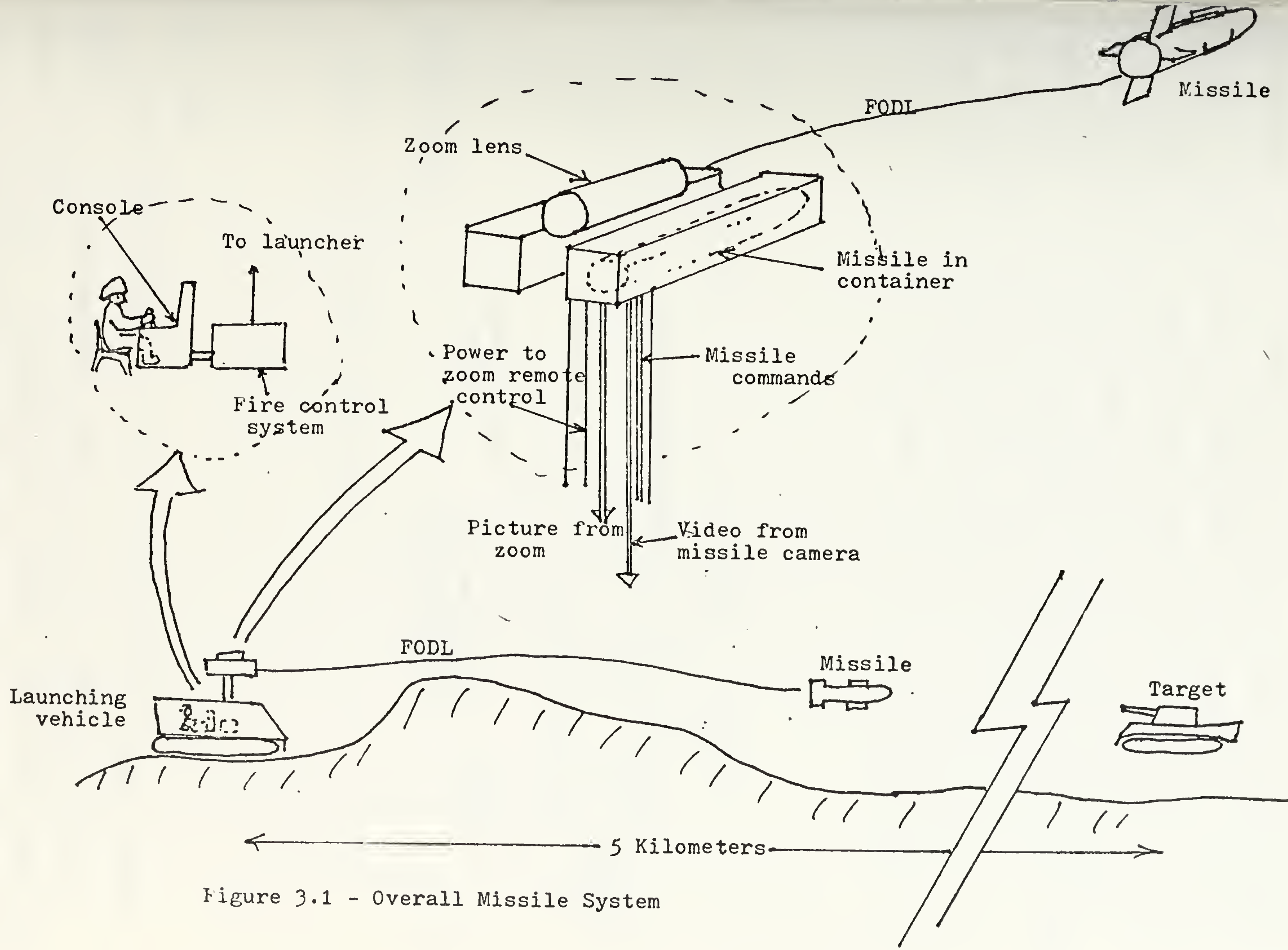


Figure 3.1 - Overall Missile System

than 30 Kg. For ease of handling, the container should not be longer than 125 cm and its diameter should be less than 25 cm. This allows the container to be handled by one man.

It has been domonstrated that the CCD camera and components can withstand accelerations in the order of 15000 G's [Ref. 13]. The shock testing was conducted successfully both in an air gun and in an eight inch (205 mm) howitzer. Similarly, it has been demonstrated that a fiber optic payout system is possible at speeds in excess of 175 m/sec [Ref. 14].

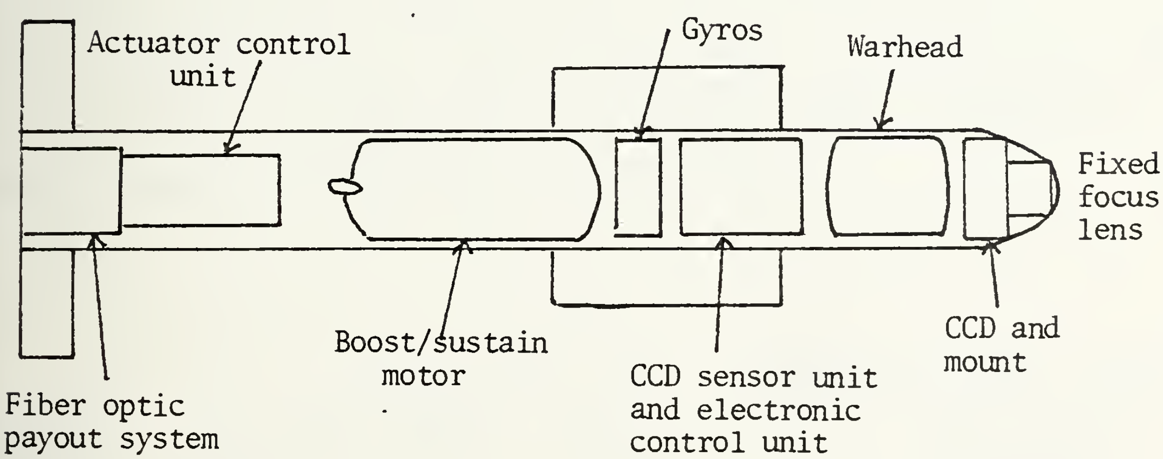


Figure 3.2 - Missile Subsystem

C. LENS

Within the Missile, as part of the CCD mounting board, there is a lens adaptor. On it, a fixed focus, 50mm lens would be mounted. Throughout the flight this would give the operator a 45 to 50 degrees field of view of the area directly

in front of the missile. Cross hairs would be etched on the center axis of the lens to assist the operator in aiming the missile.

D. CCD AND SENSOR UNIT

There are a number of CCD cameras on the market today with Fairchild and RCA being the two leading manufacturers. For this missile, the imaging system is based on the Fairchild MV 202. The camera is a digital video system based on the Fairchild CCD 211 chip. Figure 3.3 is a block diagram of the CCD Sensor Unit. The unit consists of a main camera body and a separate sensor head. The sensor head is attached to the camera body by a multi-wire cable. The mounting board is designed to accept the 24 pin CCD 211 chip. Appendix B gives the pin configuration for this CCD.

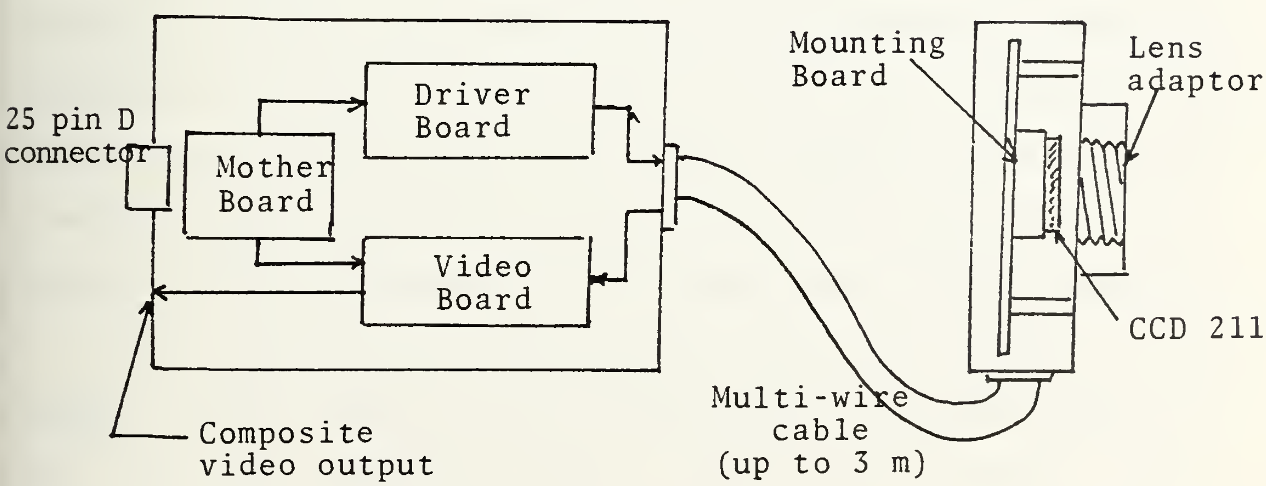


Figure 3.3 - CCD Sensor Unit Block Diagram

The main camera body is called a sensor unit which consists of three printed circuit boards. The Driver board converts a square wave master clock input into the complementary clock signal required for horizontal transport of data in the CCD sensor. It also generates the sample and hold clock needed by the CCD output circuit. The Video Processor board converts raw video input from the CCD to composite video which drives a standard television monitor. At the rear of the main camera body there is a Mother board and 25 pin D connector. This provides connections for digital and bias voltage inputs into and out of the camera boards. In addition, there is an external logic or timing control board. This board generates the timing signals required by the CCD sensor array and the TV synchronization signals required to drive a standard video monitor (horizontal and vertical counter chains drive PROMs which are programmed with these signals). The crystal controlled TV Sync Generator generates composite sync and blanking used on the video processor board. Using the TV Sync signals as a basis, the CCD Clock Generator combines with the high frequency Bit Rate Oscillator to produce the field, horizontal and element rate clocks required.

The simple logic of the driver board, the video processor board and the timing control board can be obtained from Ref. 16. The more important points to note are as follows. The 244 by 190 element sensor and the hardware product family can provide NTSC resolution over 25 percent of the TV monitor, or can be used with a non-standard TV x-y display monitor.

The 244 line vertical resolution precludes a standard 525 line video presentation. Instead, a frame consists of two 263 line fields (non-interlaced) with video presented on alternate lines. This provides interlaced video on a non-interlaced raster. The video output is composite video as shown in Fig. 3.4. Reference 17 provides additional information on what constitutes composite video (see Appendix B for the CCD 211 chip timing diagram). The video processor contains an AGC amplifier with 20 dB dynamic range. Timing signal inputs to the sensor unit are differential digital waveforms supplied to the driver board through the rear panel D connector.

Vertical transport, and field transfer of data from photosites to the CCD vertical registers are controlled by $\emptyset_V$ and $\emptyset_p$ driver board input signals (Appendix B). Sync and blanking signals are buffered on the driver board and then delivered to the video processor. The following are the timings:

- one cycle to move information to the vertical register (350 usec)
- 124 cycles to move information to the horizontal register (43.4 msec)
- 200 cycles to move information to video output.

The Fairchild MV 201/202 Camera meets the standard for closed circuit TV cameras (RS 330).

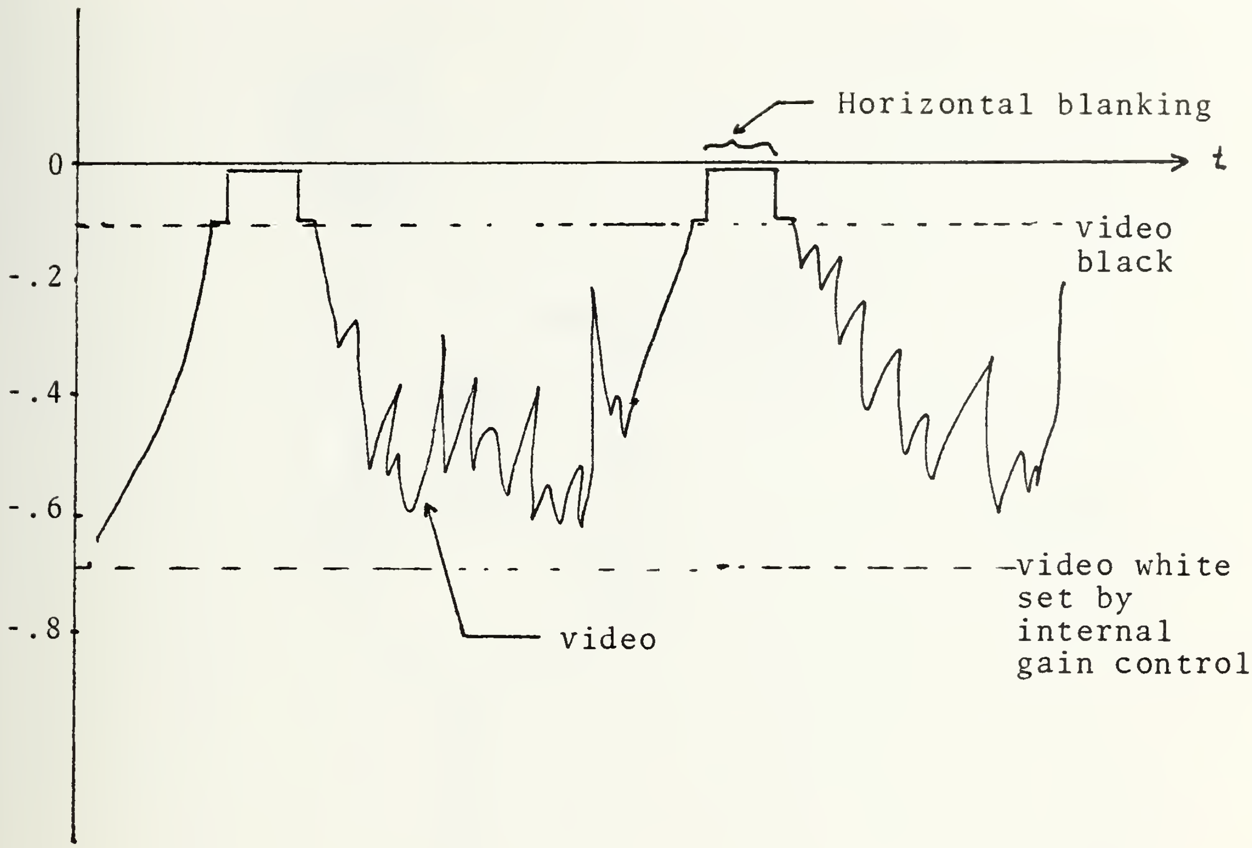


Figure 3.4 - Composite Video Output (0.7 v p-p into 75 ohms)

E. FIBER OPTIC DATA LINK

The overall FODL is shown in Fig. 3.5. Optelecom Inc., in conjunction with the U.S. Army's ECOM and now MIRADCOM, has been working for four years on a fiber payout system. The results have been successful so far but much of the detailed information is classified. It is mentioned here to note that such a system is feasible.

Generally the more complex and costly items would be designed into the launcher so that they could be used repeatedly. The cost of the expendable missile is kept as low as possible.

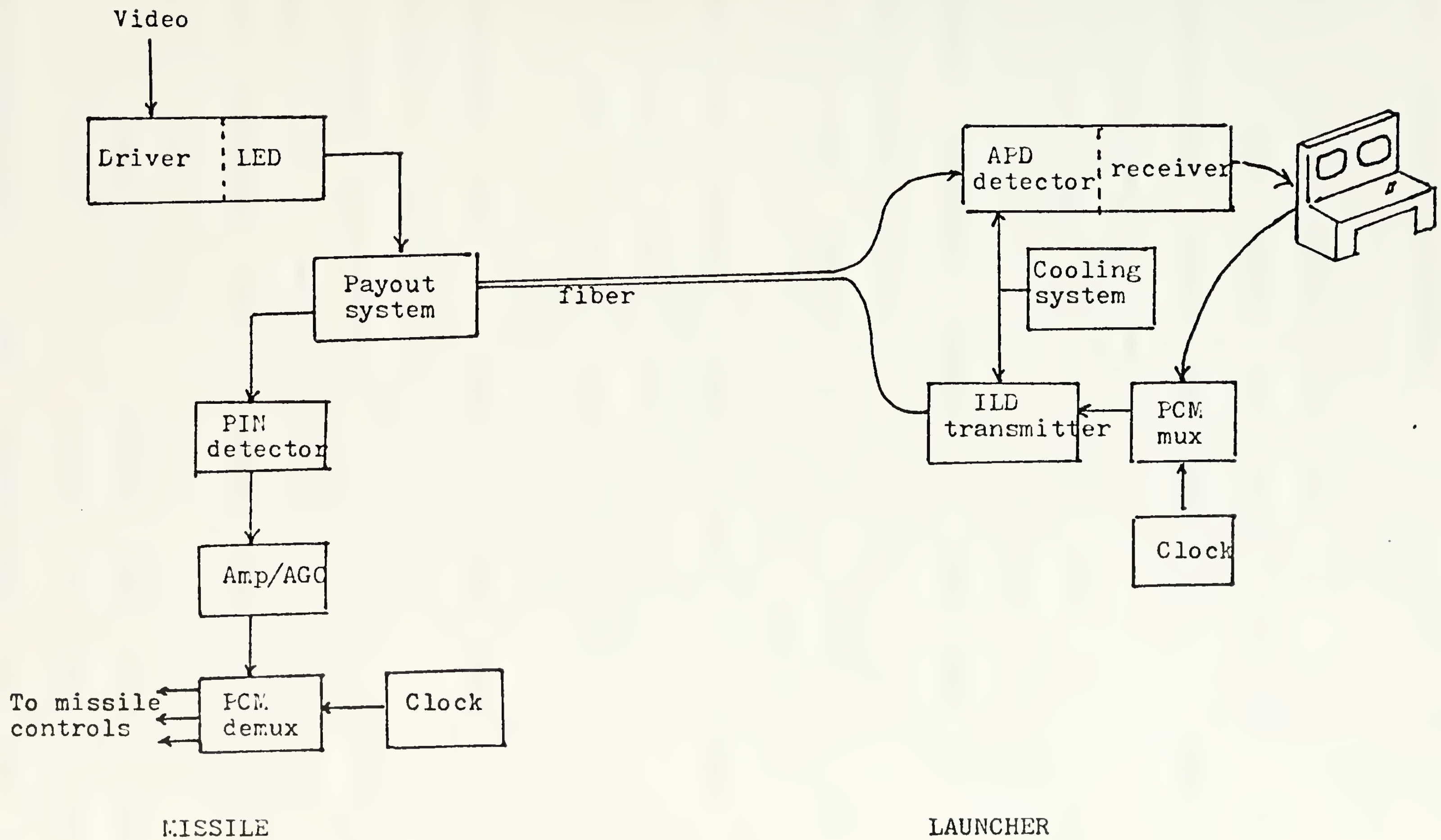


Figure 3.5 - Fiber Optic Data Link

Another important consideration is in the flight control systems, in the tradeoff between closing the control loops in the missile or in the FCS using the FODL. If the latter method is used, time becomes increasingly important, especially at the far end of the flight path due to the round trip distance information must travel. If all the control loops are closed in the FCS, then the outputs from all the on-board sensors must be digitally coded for transmission down the FODL. Commands coming up the data link from the FCS must be decoded into proper inputs for the servopositioners. In the author's system only video information is passed down the FODL. The missile receives commands from the operator via the FODL and from on-board control systems. An example of an on-board control system would be a roll attitude control loop. Roll stabilization is necessary so that the missile remains in one attitude during flight. This allows the operator to interpret the video picture so that appropriate turning signals can be transmitted.

Every attempt has been made to utilize the strong points, or advantages, of the components found in a fiber optic system. For instance, the LED source is much cheaper than the ILD source and is therefore placed in the missile. Similarly, the PIN detector is cheaper than the APD detector and is therefore placed in the missile. The LED is better for analog signals and is used in the video link while the ILD is better for digital signals and is used in the command link. The ILD and APD require temperature compensation.

Both have been placed in the launcher, thus sparing any extra weight and bulk in the missile. The APD requires larger biasing voltages and is placed in the launcher where this voltage is more readily available. The components in the missile require smaller biasing voltages which in turn mean smaller power supplies (batteries). Basically the cheaper, smaller, less complex items have been designed into the expendable missile while the larger, more expensive, more complex items have been placed in the reusable launcher.

1. Payout System

Reference 14 is one of the few unclassified reports available on a fiber optic payout system. The type of fiber found most suitable for this program was a step index fiber having a quartz core and a cladding of silicone resin. It has an outer coating of hardened plastic to provide resistance to bending caused by outside forces and to provide low friction during payout. Payout spools have been developed that work reliably at speeds in excess of 175 m/sec. Initial tests indicated that the spools add a loss of 2.5 dB/Km to the cable transmission loss. Prior to launch, the cable would be routed from the dispenser in the aft end of the missile to the launcher.

The fiber used has a large N.A. of 0.36 and a large core diameter of 125 um. The bandwidth is approximately $20/\sqrt{L}$ MHz, where L is the fiber length in Km. Fibers of this type have been made with losses as low as 3 dB/Km at

840 nm. This fiber has the highest resistance to nuclear radiation of any fiber known.

2. Down Link

The down link is for the video information. References 9 and 18 are the basis for much of the detail in this section. A schematic block diagram of a typical optoelectronic transmitter module for baseband video transmission is shown in Fig. 3.6. The most suitable LED is the Burrus type GaAS - GaAlAs double heterojunction high radiance diode. The current is confined such that the emitting area is smaller than the area of the fiber core, ensuring optimum coupling efficiency. The optical power, coupled into a step index fiber, can be calculated using the following equation:

$$Pf = \pi I_r (N.A.)^2$$

where I_r is the radiant intensity. Clearly, the higher the N.A., the higher the coupling efficiency. Reference 18 also discusses the linearity characteristics of the LED. In general, the LED offers the best performance for transmitting analog signals.

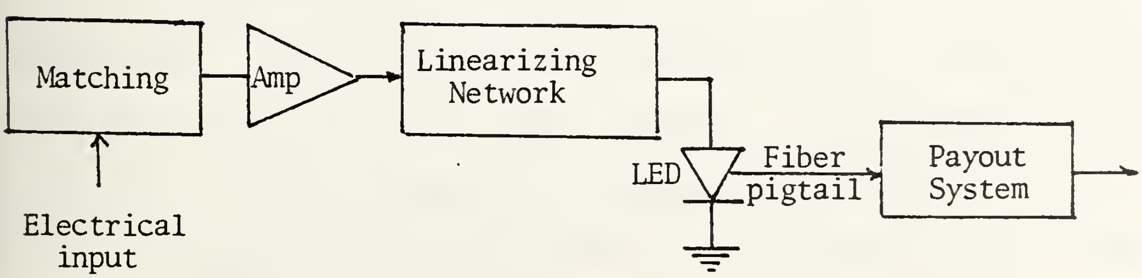


Figure 3.6 - Typical LED Transmitter Module

Figure 3.7 shows a typical APD receiver module. The received optical power is coupled to the detector face through a short, large core, step index "pigtail" fiber. The pigtail is permanently attached to the source's emitting area by the manufacturer to reduce input coupling losses. (This essentially eliminates unintercepted illumination loss because the separation between emitting surface and fiber end is reduced to less than 2 to 4 times the core diameter. There is no standard as yet so actual separations do vary.) Coupling efficiency between the pigtail fiber and the detector is approximately 80 percent (1 dB loss).

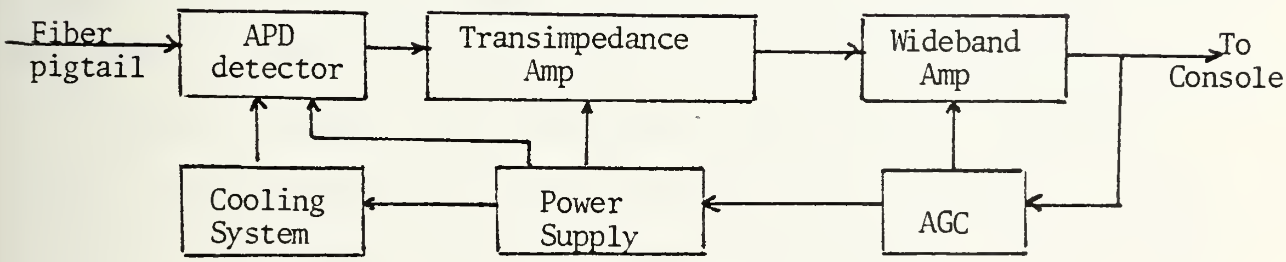


Figure 3.7 - Typical APD Receiver Module

Automatic gain control (AGC) is obtained by peak detecting. The APD control is derived from a voltage on the command line to the APD power supply. A temperature control circuit is also included to minimize any losses.

Appendix F contains detailed analysis of this link. The more important points are summarized below:

a. A pigtail arrangement is used to reduce losses;

b. The power output from an attached pigtail on the LED can approach a respectable 1 mW (0 dBm);

c. The value for required received power for the APD was chosen conservatively at -70 dBm;

d. Minimizing the temperature variations would require a compensation circuit with the APD [Ref. 11];

e. Time degradation is due to time on the storage shelf. It would be a maximum of 1 dB;

f. The system provides an excess power of 11 dB which meets the 7 dB requirement for closed circuit TV [Ref. 24].

3. Up Link

The up link transmits commands from the FCS/operator to the missile. This is a digital link utilizing TDM (Appendix D). As mentioned previously, the cheaper PIN receiver is used in the missile. To ensure sufficient power to overcome losses, the transmitter used an ILD. Semiconductor laser diodes are exceptionally well suited for use in digital fiber optic systems. Figure 3.8 shows a simple block diagram of a typical ILD transmitter and PIN receiver.

Appendix G contains detailed analysis of this link. The more important points are summarized below:

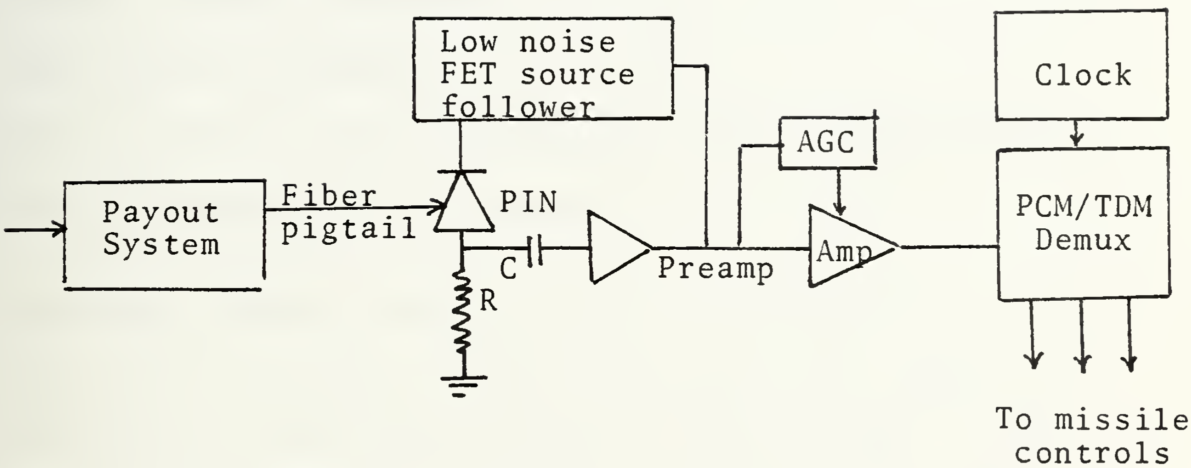
a. Again, as shown in Fig. 3.8, a pigtail arrangement is used to reduce unintercepted illumination losses;

b. The power output from an attached pigtail on an ILD can approach 14 mW (11.5 dBm);

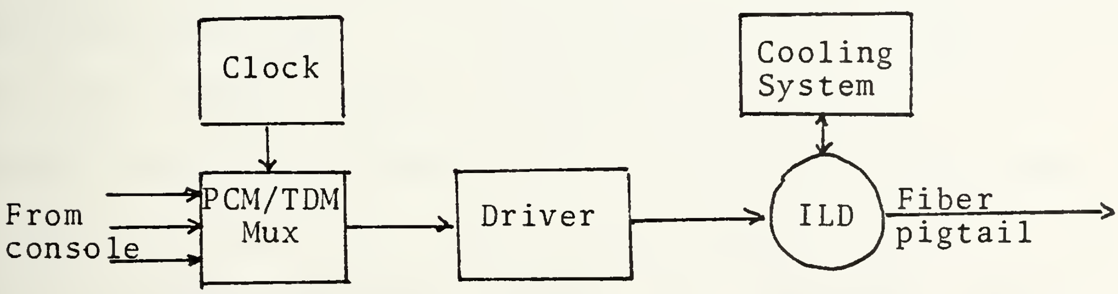
c. The value for required receiving power for the PIN was chosen conservatively at -50 dBm;

d. Time degradation is due to time on the shelf;

e. The system provides an excess power of 6.1 dB.



(a) PIN Receiver



(b) ILD Transmitter

Figure 3.8 - Block Diagram of Typical Receiver and Transmitter

Depending on the complexity of the missile system, varying numbers of commands can be passed to a missile. For this missile the following commands can be sent from the launcher:

- Elevation turning commands
- Azimuth turning commands
- Self destruct command.

However, the FODL could easily handle a more sophisticated missile with more types of commands.

F. ELECTRONIC CONTROL UNIT

Within the electronic control unit are the transmitter for the down link and the receiver for the up link. These two have already been covered and will not be discussed further. In addition, there is a requirement for on-board controls such as a microprocessor. It would carry out the following functions. It would activate the on-board batteries once the prefire trigger signal was received (batteries are solid-electrolyte thermal type). It would activate the attitude control gyro once the prefire trigger signal was received. The microprocessor would activate the CCD Sensor System once the batteries were fully activated and the boost motor once the CCD Sensor System was activated. It would activate the flight sustaining motor once the missile had reached a speed of 150 m/sec, thus ensuring the missile was clear of the launcher before the sustaining motor was fired. It would arm the warhead if the flight motor was fired and would

continue throughout the flight to interpret commands received and activate the appropriate control mechanisms such as the actuator system.

The Electronic Control Unit also contains the amplifiers and discriminators necessary for the internal control of this missile. For instance, the signals from the gyro are shaped and superimposed on the missile steering signals to produce missile roll stabilization and initial yaw stabilization.

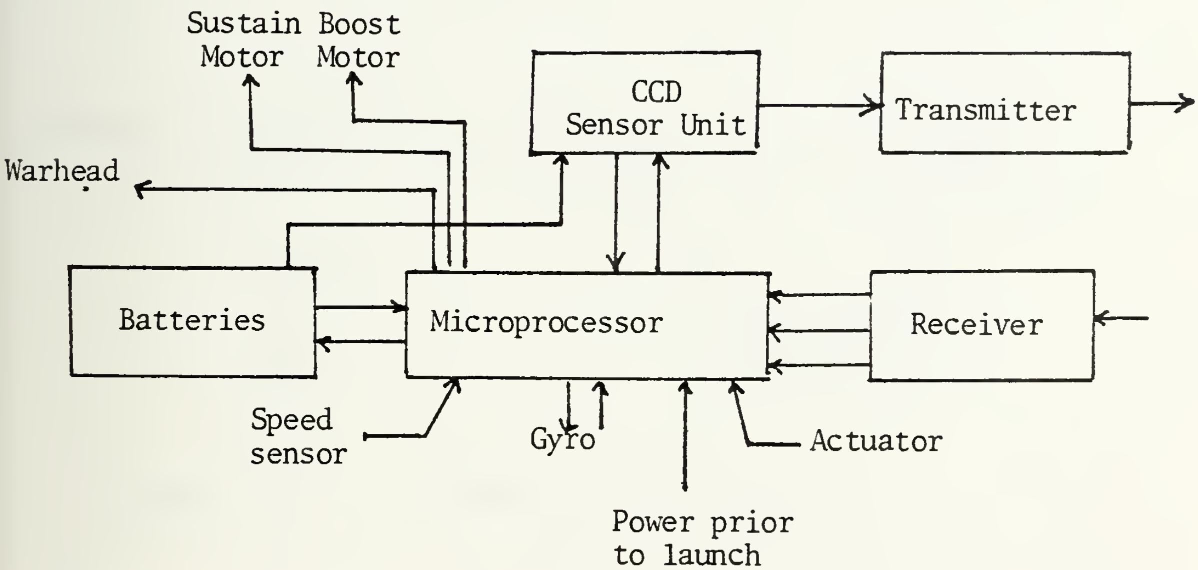


Figure 3.9 - Electronic Control Unit

G. LAUNCHER SUBSYSTEM

The second major portion of the missile system is the launcher subsystem. Figure 3.10 is a block diagram of the launcher. It consists of the following subsubsystems:

1. Missile Guidance Set - section III.H;
2. Control/Video Console - section III.I;
3. Zoom Lens - section III.J;

4. Launch Pedestal - no further discussion;

5. Power Supply - no further discussion.

The launcher is restricted in size in that it must fit on a single military vehicle similar to the M113 Armored Personnel Carrier presently used by the U.S. Army. For ease of maintenance, each assembly must be capable of being disassembled by a two man crew. The possibility of dismounted operations will not be discussed here.

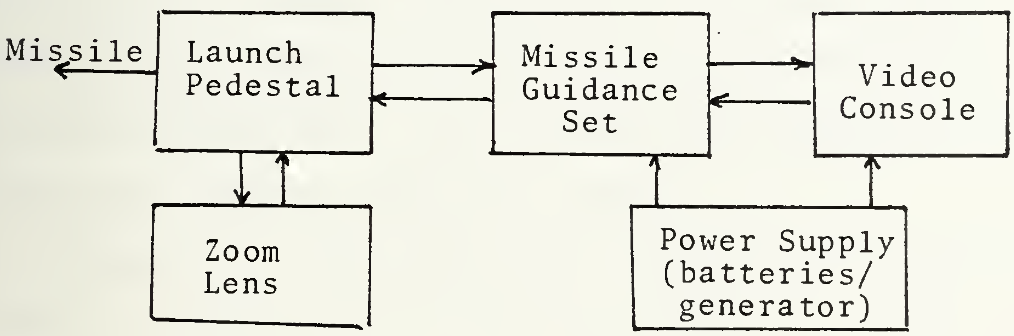


Figure 3.10 - Launcher Block Diagram

H. MISSILE GUIDANCE SET

The missile guidance set is a self-contained system powered by a battery or generator, depending on operational requirements. It provides steering information to the missile in response to commands received from the video console. Left, right, forward and backward movements of the joystick in the console are converted into pitch and yaw error signals. The yaw error signal is applied to the yaw command signal generator where it is combined with a signal from the azimuth

rate tachometer generator. The tachometer generator provides a voltage proportional to the rate of lateral motion of the target. This assists the operator in following fast moving targets. Similarly, a combined pitch error signal and a signal from the elevation tachometer generator are passed to the multiplexer. Both sets of signals are Pulse Code Modulated (PCM) and time division multiplexed for transmission to the missile via the FODL.

The video picture is passed to the console from the fiber via the APD receiver. To ensure an adequate signal to noise ratio at the console, a low noise preamplifier is situated in the guidance set. This allows more freedom in positioning the video console within the vehicle.

Figure 3.11 shows the block diagram of the guidance set. The ILD Transmitter, the APD Receiver, the cooling system and the PCM/TDM Multiplexer have been discussed elsewhere. For operations requiring extreme quiet (night operations), the battery would be used. The battery would be a standard nickel-cadmium type, a proven technology for field use. During normal operations, an external generator would charge up the batteries.

I. VIDEO CONTROL CONSOLE

Figure 3.12 shows a possible video control console. The console receives a video picture from the camera on the front of the missile. The operator must keep the target in the square to assure himself of a hit. The console also receives

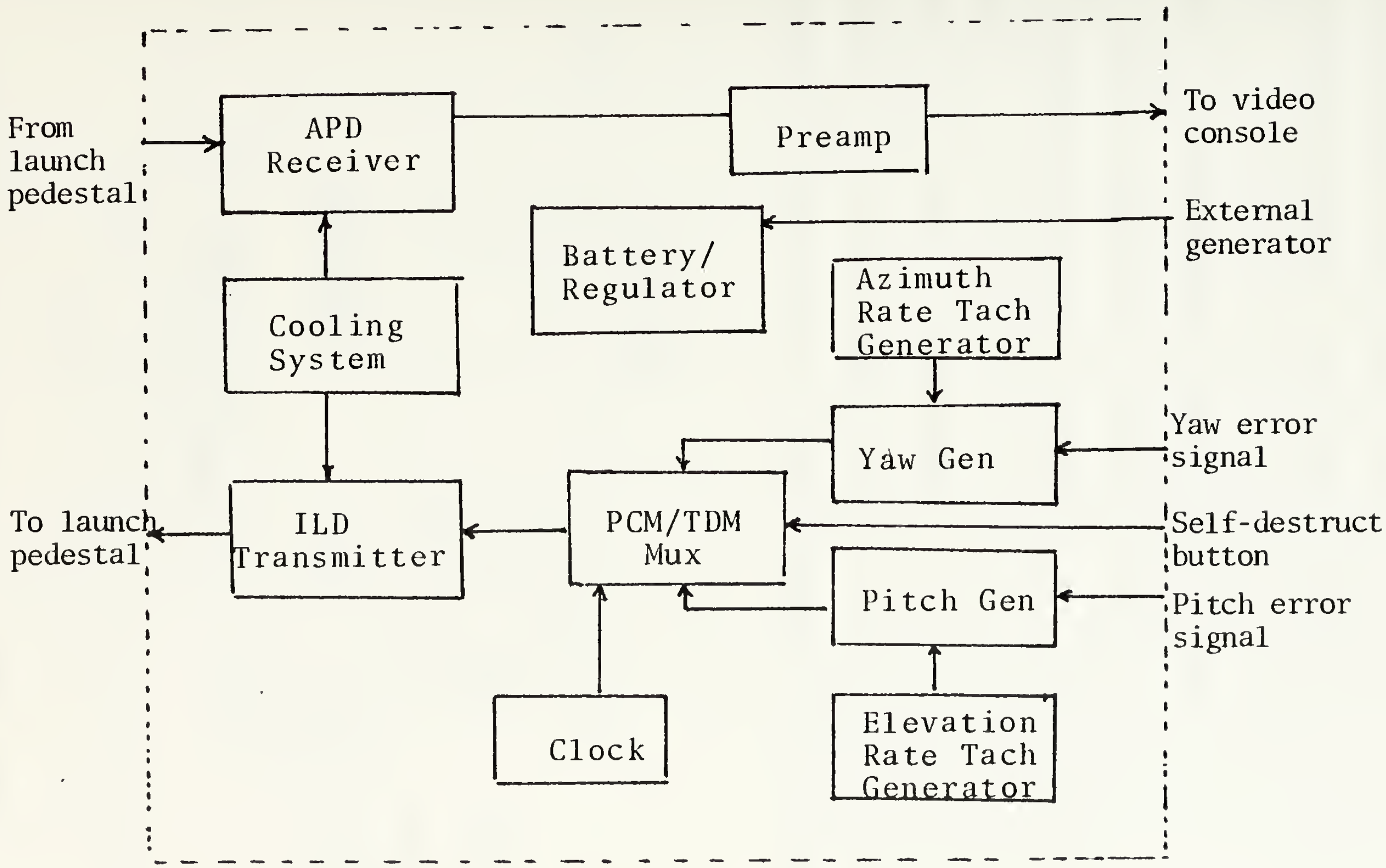


Figure 3.11 - Block Diagram of Missile Guidance set

a video picture from the zoom lens mounted on the launch pedestal. The operator can raise the launch pedestal and thus the zoom lens, and then rotate it to give himself a view of the battlefield. He could "zoom in" to identify a target. He would use this picture to fix his missile relative to the target and relative to himself.

The console passes yaw and pitch error signals to the missile guidance set due to movement on the joystick by the operator. If the operator wants to destroy the missile while in flight due to a malfunction, he would press the self-destruct button on the joystick. A predetermined pulse code received at the missile would detonate the warhead.

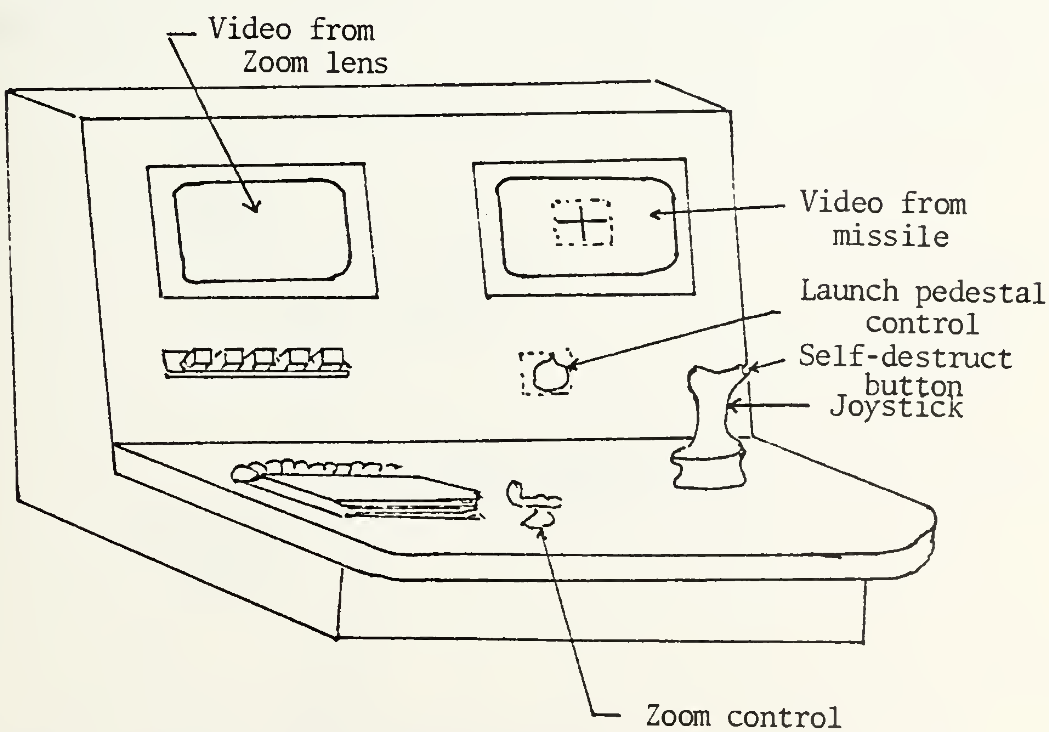


Figure 3.12 - Video Control Console

J. ZOOM LENS

To increase the launch range of the missile, a zoom lens could be attached to the launch pedestal. The lens would be aligned with the missile longitudinal axis. As noted in Ref. 15, there are special lenses made for closed circuit TV with a focal length of 15 to 150 mm and maximum relative aperture of f/2.5. The lens gives a horizontal angle of viewing of 100° to 21° (assuming a 2-1/4 by 2-1/4 display). The remote control portion of the lens employs a d.c. motor which has the advantage of small size and low running speed. Because the motor requires only 3 VDC to operate, it is not subject to arcing and consequently does not require spark suppression circuitry. Figure 3.13 shows a basic block diagram of the zoom lens electrical circuit.

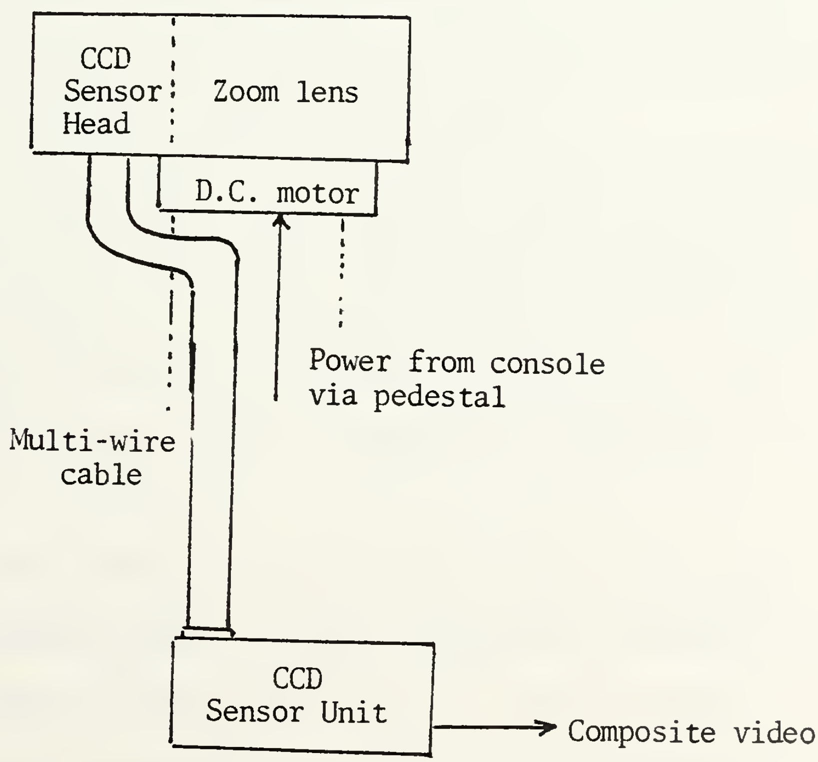


Figure 3.13 - Zoom Lens Remote Control

IV. FUTURE DEVELOPMENTS

Most military equipment is considered obsolete by the time it comes off the end of the production line and is distributed to the user. This is due partially to the rapid advancements in technology. The system proposed in the previous section would be no exception. However, as requested in the needs analysis, room has been left for improvements. Discussed below are some of the possibilities for improving the system.

A. NIGHT CAPABILITY

One of the most important features required on any missile system is a passive nighttime capability. This suggests using Forward Looking Infrared (FLIR) devices as now employed on the Night Maverick and the Night Walleye.

Reference 23 outlines the two major classes of FLIR IRCCDs. The monolithic IRCCD fabricates both the photosensitive IR array and the readout section (CCD) within one structure. The hybrid IRCCD consists of devices in which the major functions occur in distinct but integratable components and materials.

However, these chips, dispite their improved capabilities, do have some limitations. A major difference between the operation of CCDs in the visible and in the IR range is the large background flux rate in the IR. This results in

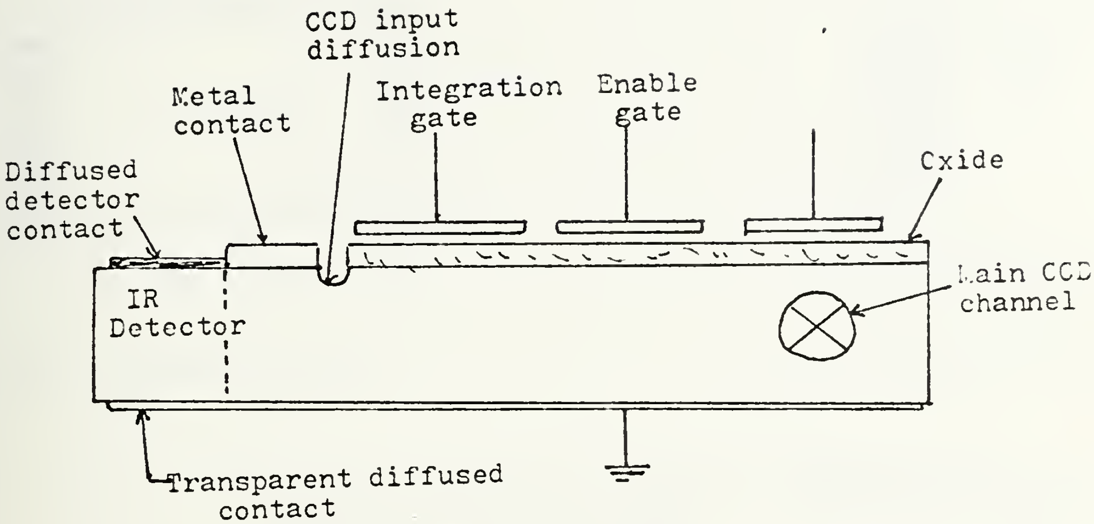
increasingly shorter background charge-up or saturation time with increasing wavelength of operation. Thus, one limitation of practical IRCCD devices is the length of exposure time.

Another practical limitation is in the small contrast between photon flux generated by temperature variation in the background and total photon flux. For a 0.1°K variation in the 300°K background, the contrast is in the order of 1 percent in the 2.0 to 2.5 um window and less than 0.1 percent in the 8 to 14 um region. Both of the above problems are reduced by using Time Delay Integration (TDI) operations. Figure 4.1 shows an example of a monolithic and hybrid IRCCD.

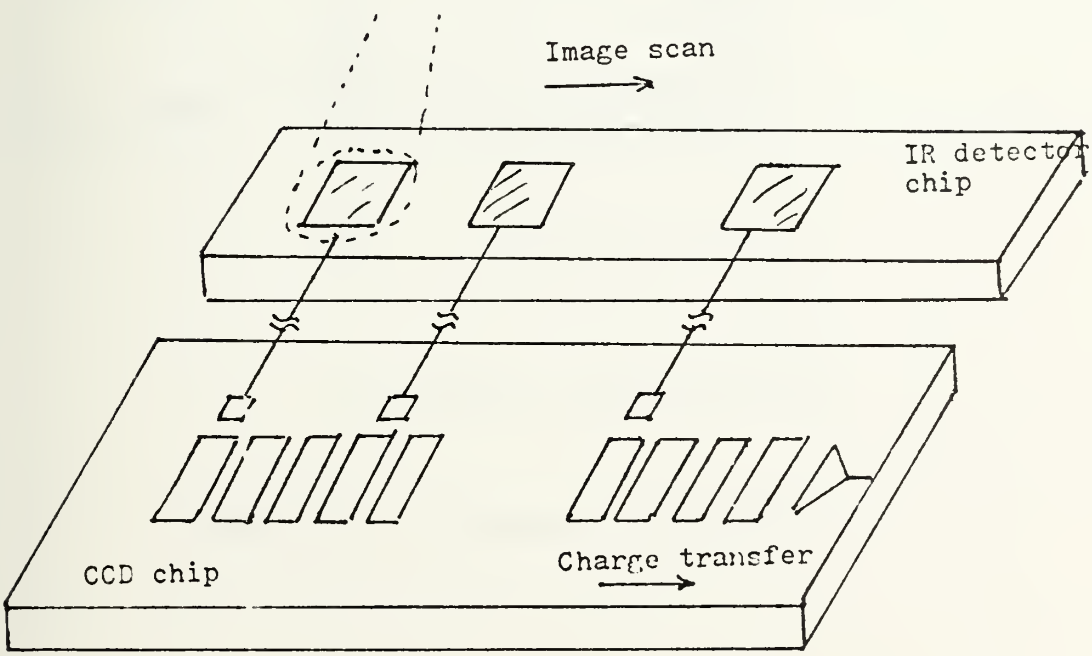
Another possible approach to improve low light level capabilities is noted in Ref. 27. Electron Bombardment (EB) CCDs introduce prestorage gain by detecting the light with a photocathode and then accelerating the photoelectrons so that many secondary electrons are generated when they strike the CCD. Figure 4.2 shows some examples of EB-CCDs. Theoretically the EB-CCD would give an order of magnitude improvement in sensitivity. The limitation is more bulk, bigger lenses and higher voltages.

B. LONGER RANGE

The second most important feature is improvement of the range of the missile system. The proposed system has a range of 5 Km. Increasing the range increases the probability of survival of the launcher.

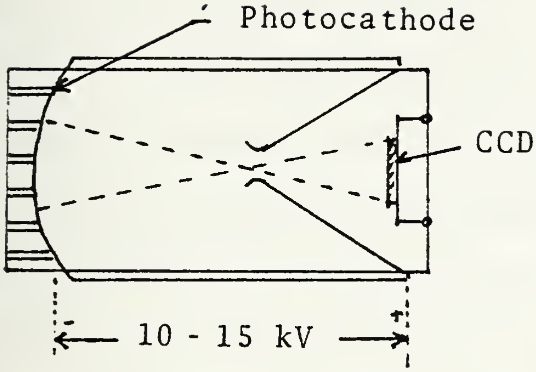


(a) Monolithic IRCCD : Horizontally Integrated Structure

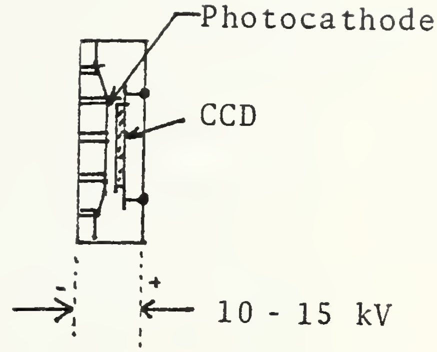


(b) Hybrid IRCCD : TDI Serially Scanned Operation

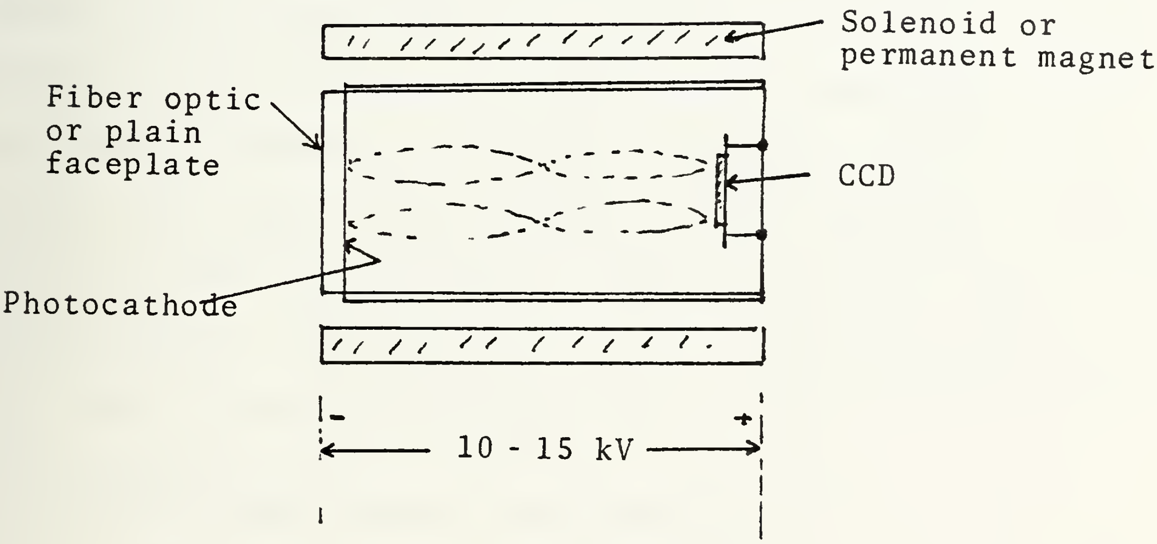
Figure 4.1 - Examples of IRCCDs



(a) Inverter EB-CCD



(b) Proximity EB-CCD



(c) Magnetic focus EB-CCD

Figure 4.2 - Examples of EB-CCDs

The two main areas that must be improved to increase the range are the CCD sensitivity and the attenuation losses in the fiber. Both must be tackled for a significant improvement in range. As noted previously, the TDI CCDs are capable of extremely low contrast performance by virtue of the spatial noise averaging in the TDI process. It is expected that a TDI device with 128 steps of integration will facilitate imaging at contrast levels less than one-tenth that of conventional CCD imagers. This degree of improvement could extend the viewing range by 60 percent. To improve attenuation, it is necessary to move to higher wavelengths. As sources and detectors become more reliable in the 1.3 um region, the range of the system could be increased. In addition, it should be possible to reduce attenuation due to the payout spool. This presently adds 2.5 dB/Km attenuation to the cable transmission losses.

C. BETTER SEARCH/ACQUISITION CAPABILITY

The system presently being developed for the U.S. Army will have a limited search capability. This will give the operator an indirect fire capability if he knows approximately where the target is located.

The FODL is capable of handling additional information in both links. Additional sensors could be added to the missile subsystem with very little increase in complexity and cost. For instance, a "push broom scan for one-dimensional array" system similar to the one noted in Ref. 29,

could be included in the proposed missile system. Indirect fire would also increase the probability of survival of the launcher.

D. COLOUR VIDEO

The bandwidth of the FODL is more than sufficient to handle colour TV. Colour would increase the probability of detecting targets. However, the author has found very little written about the use of colour with CCD imagers. One of the few articles found [Ref. 30] indicates that the improvement in sensitivity is marginal compared to the increased complexity of the system. Further improvement in colour CCD technology is required before it is placed in a missile. Once the technology is improved, it could easily be incorporated.

E. AUTOCUEING AND AUTOLOCK-ON

These two features could be added if the missile is given an acquisition capability. Much research has been directed at computer-aided pattern recognition technology. The goal of an autocuer for an imaging target acquisition system is to provide cues to the operator by highlighting objects in the video which may be targets. Automatic lock-on relies on a processor making use of model matching techniques. These require stored models of the expected targets which are matched to elements in the video by the automatic lock-on software. Thus, a launch and leave capability would be given to the missile. Studies are still underway at MIRADCOM to balance improved performance versus increased cost and complexity.

F. PHOTODIODE ARRAY CAMERA

Reticon Inc. manufactures a 100 x 100 Matrix Camera (Model MC520) utilizing photodiode arrays. They claim it is superior to the CCD in sensitivity and spectral uniformity because it does not require the use of a semi-transparent electrode. Further study is required to verify their claim.

There are many other possibilities that could improve this system but lack of technical information does not allow this paper to give them fair treatment. As noted in Appendix E, the use of new unproven technology involves a high risk and requires that the system engineer note carefully the probability of success.

V. CONCLUSIONS

The obvious conclusion of any feasibility study is that the system is or is not feasible. The author's conclusion is that the system is feasible and has the following advantages:

A. MILITARILY

The probability of first round kill can be increased by using a video signal and directing the missile at the target until impact. The system's effectiveness is improved by minimizing multiple missile assignment to the same target. By increasing the range of the missile, the operator is able to engage the target at ranges in excess of the target's main armament. An indirect fire capability could be added with minimum modification.

B. TECHNICALLY

The system utilizes the latest state-of-the-art in fiber optic and CCD imaging technology. It uses the higher reliability of solid state technology. Technical improvements can be made with minimum requirement for major modifications.

C. ECONOMICALLY

The cheaper components have been designed into the expendable missile. The more complex and costly components have been designed into the reusable launcher. Some of the technology developed can be utilized by the commercial market which would offset some of the research and development costs.

APPENDIX A

GLOSSARY OF SOLID STATE IMAGING TERMS

1. Backside Illumination

   CCD fabrication technique employing "thinned" silicon where the image is impressed on the side opposite the MOS electrode.

2. Bucket Brigade

   Technique of building a photosensing array using FETs. Two FET amplifiers are at each sensing area and are interconnected as an element of a shift register.

3. Buried Channel

   Thin doped layer in silicon just below the oxide to prevent trapping of charges.

4. Charge Coupled Device (CCD)

   Employs a charge transfer system in which charges created by either an input diode or by an impinging photon is contained in MOS capacitors fabricated on a single crystal wafer. By varying electrode voltages successively, charge packets are moved from capacitor to capacitor to a single output diode.

5. Channel Diffusion Stops

   A narrow doped region beside each sensing channel that prevents excess charges generated within a particular light sensing site from spreading sideways.

6. Fat Zero

   In surface channel CCDs, charges tend to be captured by surface effects, thus resulting in a loss of signal. By continuously introducing a charge into all CCD channels through a diffusion at the beginning of the channel, the areas that trap charges are filled by the induced charges

rather than the signal charges, thus increasing transfer efficiency.

7. <u>Integration Time</u>
   Time during which all electrons formed by impinging photons are gathered in a potential well under an energized electrode.

8. <u>Interlace Frame Transfer</u>
   CCD configuration where all charges accumulated during an integration period are rapidly moved out of the optically active area. The shielded readout channels are located side by side with the active channels. Following the integration time, the stored charges are moved sideways to the readout channels where they are successively read out during the next integration time.

9. <u>Surface Channel</u>
   Potential well of a CCD is formed at the Si - SiO_2 interface and the charge transfer occurs near the interface.

10. <u>Transfer Efficiency</u>
    Percentage of total charge that is transferred from one position to another during readout.

11. <u>Vertical Frame Transfer</u>
    CCD configuration where all charges accumulated during an integration period are rapidly moved out of the optically active area and to an identically shielded CCD area where it is read out at a slower pace during the next integration period.

APPENDIX B: PRELIMINARY DATA SHEET CCD 211

CCD211

244 × 190 ELEMENT AREA IMAGE SENSOR

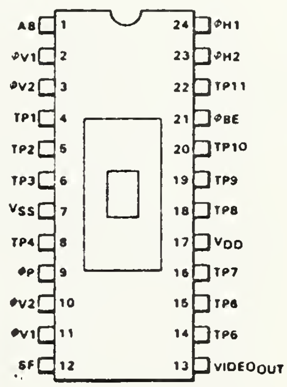
CHARGE COUPLED DEVICE

GENERAL DESCRIPTION The CCD211 is a solid state self-scanned area image sensor suitable for use as the sensor in camera type applications The device is organized in an array of 244 horizontal lines by 190 vertical columns The 46.360 image sensing elements are 14 μm horizontally by 18 μm vertically and are located on 30 μm horizontal centers and 18 μm vertical centers The dimensions of the image sensing area are 4 4 mm x 5 7 mm with a diagonal dimension of 7 2 mm

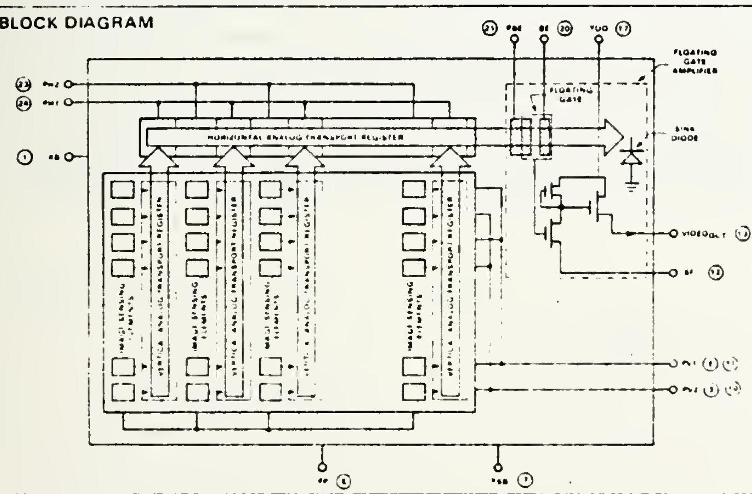
The X-Y format of the array was selected to provide a 4 x 3 image aspect ratio and to approximate the image size of the Super 8 movie lenses The highly precise location of the photosites allows precise identification of each component of the image signal This feature allows the device to be used in applications requiring precise dimensional measurement The device is also intended to be used in video cameras that require low power, small size, high sensitivity and high reliability. The device is packaged in a 24-pin Dual In-line Package with an optical glass window.

- 46.360 IMAGE SENSING ELEMENTS ON A SINGLE CHIP
- COLUMN ANTI-BLOOMING
- NO LAG, NO GEOMETRIC DISTORTION
- GAMMA CHARACTERISTIC OF APPROXIMATELY 1.0
- ON-CHIP VIDEO PREAMPLIFIER PROVIDING MORE THAN 200 mV OF OUTPUT SIGNAL
- HIGH DYNAMIC RANGE – TYPICALLY: 300:1
- LOW LIGHT LEVEL CAPABILITY, LOW NOISE EQUIVALENT EXPOSURE
- WIDE RANGE OF VIDEO DATA RATES UP TO 100 FRAME/s
- ALL OPERATING VOLTAGES UNDER 20 V
- LOW POWER DISSIPATION – TYPICALLY 75 mW
- HIGH RELIABILITY
- DESIGNED TO MATCH SUPER 8 MOVIE LENSES

CONNECTION DIAGRAM
DIP (TOP VIEW)



BLOCK DIAGRAM



PIN NAMES

AB	Anti-blooming Bias
SF	Source of Floating Gate Amplifier
$VIDEO_{OUT}$	Video Output
Φ_P	Photogate Clock
Φ_{V1} Φ_{V2}	Vertical Analog Transport Register Clocks
Φ_{H1} Φ_{H2}	Horizontal Analog Transport Register Clocks
BE	Bias Electrode
Φ_{BE}	Bias Electrode Clock
V_{DD}	Power Supply
V_{SS}	Ground
TP1 TP11	Test Points

464 ELLIS STREET, MOUNTAIN VIEW, CALIFORNIA 94042 (415) 962-5011/TWX 910-379-6435

FAIRCHILD

ABSOLUTE MAXIMUM RATINGS

Operating Temperature	25 C to 55°C
Storage Temperature	25 C to 100°C
VOLTAGES	
Pins 1, 4 12, 13, 14, 17	0 6 V to +15 V
Pins 2 3, 6 8 9, 10, 11, 21, 23 and 24	10 V to +15 V
Pins 5, 7, 15, 16 18, 19, 20, 22	V_{SS} = 0 V

Caution The device has limited built in gate protection Static charge build up should be minimized

FUNCTIONAL DESCRIPTION The CCD211 consists of the following subsections as illustrated in the Block Diagram on the previous page

1 46,360 image sensing elements in a 244 x 190 array
2 190 columns of 122-element 2-phase vertical analog transport registers
3 A 200 element 2-phase horizontal analog output shift register charge coupled to the output of each of the 190 column shift registers
4 A two stage low noise floating gate preamplifier which detects and converts the charges delivered from the horizontal analog transport register to the output terminal $VIDEO_{OUT}$

Light energy incident on the image sensor elements generates a packet of electrons at each sensing element Electrical clocking of the photogate, the vertical analog transport registers, and the horizontal analog output register sequentially delivers the charge packets to the preamplifier Detailed descriptions of the functional subsections follow

Image Sensing Elements – Image photons pass through a transparent polycrystalline silicon gate structure and are absorbed in the single crystal silicon by hole-electron pair production The resulting photoelectrons are collected in the photosites during the HIGH state of the photogate. The amount of charge accumulated is a linear function of the incident illumination intensity and of the integration period The output signal voltage ranges from a thermally generated background level in the absence of illumination to a maximum at saturation

Vertical Analog Transport Registers – At the end of an integration period, the charge packets are transferred out of the array in two sequential fields of 122 lines each When the photogate voltage is lowered, alternate lines of charge packets are transferred to their corresponding sites in the vertical registers (*i.e.*, the odd numbered photoelements in the block diagram). Clocking of the vertical register at ϕ_{V1} and ϕ_{V2} delivers the charge packets from the 190 vertical registers to the horizontal analog transport register A minimum of 124 vertical transfers (124 clock cycles) are required to transport each field of charge packet out of the vertical registers. Subsequent to the removal of one field of charge packets, a second field cycle is initiated to receive the information from photosites corresponding to the other field (*i.e.*, the even numbered photoelements). Clocking of the register transports the charge packets in a similar fashion to the output

Horizontal Analog Transport Register – The horizontal register is a 200-element 2-phase register that receives the charge packets from the vertical transport registers line by line As each row of information is received from the vertical registers it is serially moved to the output amplifier by the horizontal clocks ϕ_{H1} and ϕ_{H2} A minimum of 200 horizontal clock pulses are required to complete transfer of one row of information to the floating gate amplifier

Floating Gate Amplifier – The charge packets from the horizontal register are sensed by a floating gate whose potential changes linearly with the quantity of signal charge and which drives a first MOS transistor The output signal from the transistor in turn drives the gate of an output n-channel MOS transistor which produces the video output signal at terminal $VIDEO_{OUT}$.

DC CHARACTERISTICS: T_A = 25°C

SYMBOL	PARAMETER	RANGE MIN	RANGE TYP	RANGE MAX	UNITS	CONDITIONS
V_{DD}	DC Supply Voltage		12	15	V	
V_{AB}	Anti Blooming Bias Voltage	2 0	5 0	15	V	Note 1
V_{SF}	Source of Floating Gate Amplifier	5 0	8 0	10	V	Note 9
TP1, TP3 TP4 TP5	Test Points		15		V	
TP2 TP6, TP7, TP10, TP11	Test Points		0		V	
TP8, TP9	Test Points		No Connection			

CLOCK CHARACTERISTICS T_A 25 C

SYMBOL	PARAMETER	RANGE MIN	RANGE TYP	RANGE MAX	UNITS	CONDITIONS
$V_{\phi PL}$	Photogate Clock LOW		0.0		V	$C_{\phi P}$ = 1250 pF
$V_{\phi PH}$	Photogate Clock HIGH		5.0	10	V	$C_{\phi P}$ = 1250 pF
$V_{\phi BEL}$	Bias Electrode of FGA Clock LOW		-5.0		V	
$V_{\phi BEH}$	Bias Electrode of FGA Clock HIGH		5.0	10	V	
$V_{\phi H1L}$, $V_{\phi H2L}$	Horizontal Analog Transport Register Clock LOW		-5.0		V	$C_{\phi H1} = C_{\phi H2}$ = 115 pF
$V_{\phi H1H}$, $V_{\phi H2H}$	Horizontal Analog Transport Register Clock HIGH		5.0	10	V	$C_{\phi H1} = C_{\phi H2}$ = 115 pF
$V_{\phi V1L}$, $V_{\phi V2L}$	Vertical Analog Transport Register Clock LOW		-5.0		V	$C_{\phi V1} = C_{\phi V2}$ = 1250 pF
$V_{\phi V1H}$, $V_{\phi V2H}$	Vertical Analog Transport Register Clock HIGH		5.0	10	V	$C_{\phi V1} = C_{\phi V2}$ = 1250 pF
$f_{\phi H1}$, $f_{\phi H2}$	Horizontal Analog Transport Register Clock Frequency	0.5	7.0	15	MHz	Note 2

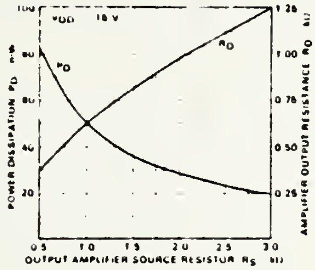
AC CHARACTERISTICS: T_A = 25°C, $f_{\phi 1H} = f_{\phi 2H}$ = 7.0 MHz. Light source is 2854°K Tungsten illumination with a Corning 1-75 IR filter.

SYMBOL	PARAMETER	RANGE MIN	RANGE TYP	RANGE MAX	UNITS	CONDITIONS
DR	Dynamic Range	200	300			Note 3
SE	Saturation Exposure	0.1	0.2		μJ/cm²	Note 4
V_{SAT}	Saturation Output Voltage	100	200		mV	Note 5
R	Responsivity		1.0		V/μJcm⁻²	
HR	Horizontal Resolution		142		L/PH	Note 6
VR	Vertical Resolution		244		L/PH	Note 6
CB	Column Blooming		20		%	Note 7
S	Shading		5.0		%	Note 8
DS	Average Peak Dark Signal		0.6		mV	Note 10

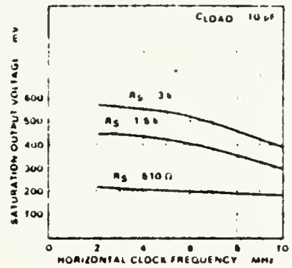
NOTES

1. Adjustment is required over the indicated range for optimum anti blooming operation.
2. Clock rates shown are typical rates at which the device operates. Operation of the devices at lower or higher frequencies will not damage the device. Three factors [illegible] to the fundamental low frequency limit: a) Integration time b) Dark current contributions from the photosites and associated dark current non uniformities c) Dark current contributions in the register which will result in an average dark signal at the output.
3. Measured by adjusting incident illumination to the signal saturation point, then attenuating the incident light with a neutral density filter [illegible] N.D. = 2.3 (which corresponds to a reduction in incident light of 200 times). The resultant off chip video signal should be [illegible] 0.5 mV_{p-p}.
4. 1 μJ/cm² = 0.02 fc·s at 2854 K
   1 fc·s = 50 μJ/cm² at 2854 K
5. Measured with a 100% contrast bar pattern as a test target. The saturation level is where the video peaks just start to flatten out as the [illegible] is increased.
6. L/PH = lines per picture height. Measured using a standard E.I.A. resolution chart as a target.
7. Measured with a point source of incident illumination level of 1000 times saturation light level and with a diameter of approximately 6 elements. Blooming [illegible] percent of the width of the bloomed column to the width of the [illegible].
8. Measured with an incident light level which produces a video output equal to $V_{sat}/2$ (50% saturation). Shading is defined as the slow variation of photosite response across a line or a field. It is expressed as a percentage variation relative to the V_{sat} level. Measurement does not include outermost rows or columns of sensors.
9. Adjustment is required in the range of 5.0 to 10.0 V for optimum operation.
10. This is the value of the dark current peaks averaged over all elements.

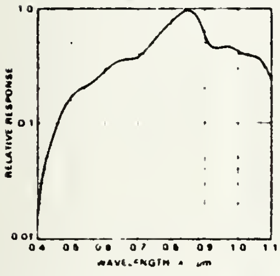
AMPLIFIER POWER DISSIPATION AND OUTPUT RESISTANCE VERSUS EXTERNAL SOURCE RESISTOR, R_S



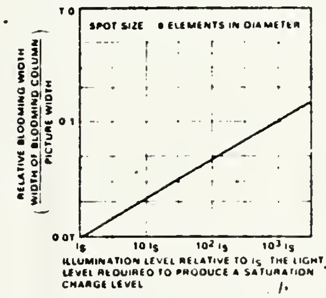
SATURATION OUTPUT VOLTAGE VERSUS DATA RATE AND OUTPUT SOURCE RESISTANCE



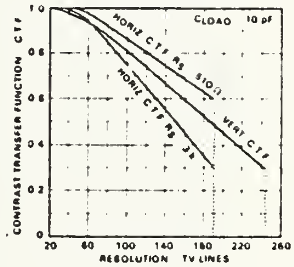
SPECTRAL RESPONSE



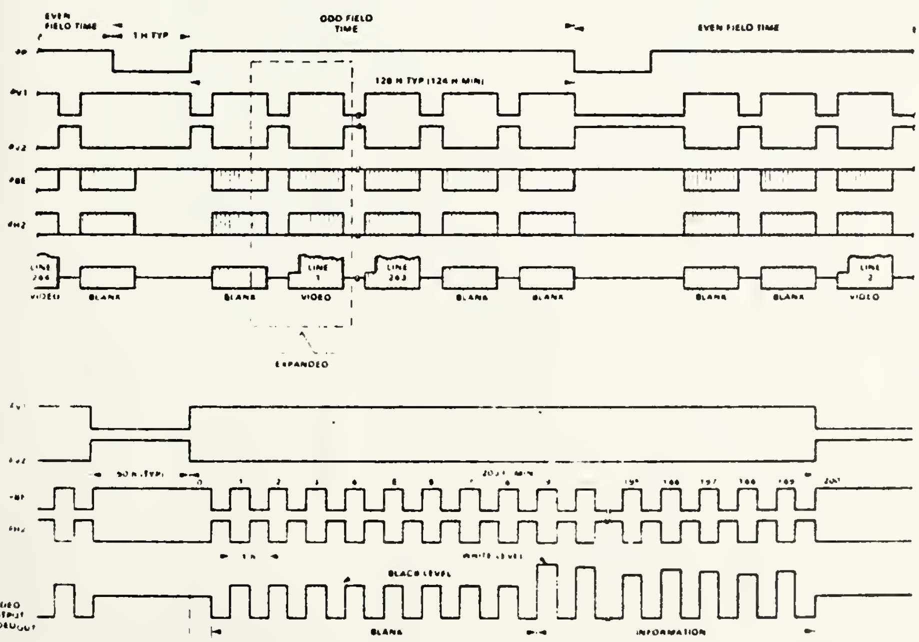
BLOOMING CHARACTERISTICS



CONTRAST TRANSFER FUNCTION

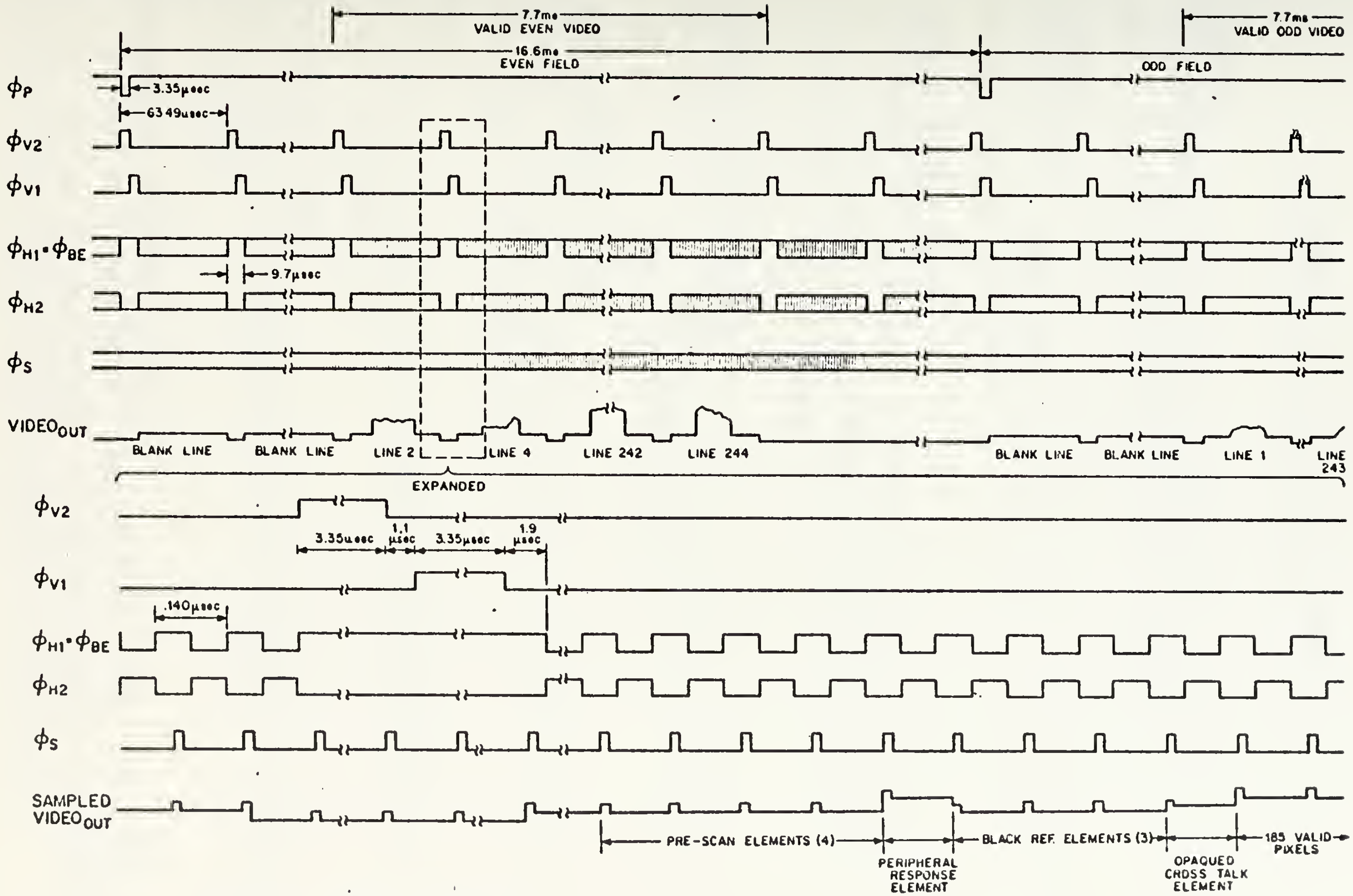


TIMING DIAGRAM DRIVE SIGNALS



NOTE All rise and fall time for all clocks should be greater than 15 ns typically for minimum clock coupling

NOTE: DEVICE IS TESTED AT F_{ϕ_R} = 7.16MHz. Times shown here correspond to this clocking frequency which is NTSC compatible.



CCD211 TIMING DIAGRAM

APPENDIX C

GLOSSARY OF FIBER OPTIC TERMS

1. Cladding
   The coating on the fiber, necessarily having a lower index of refraction than the core (fiber).

2. Dispersion
   Increase in bandwidth of light pulse while transversing the length of the fiber.

3. Graded-Index Fiber
   One where the index of refraction varies in the fiber, usually decreasing approximately parabolically from the center to the surface.

4. Index of Refraction
   The ratio of the velocity of light in a vacuum to the velocity of light in the material.

5. Microbending Loss
   Losses induced by local lateral microdisplacements of the fiber from a mean axis.

6. Modes
   Allowed solutions to a mathematical description of light propagation.

7. Multimode Fiber
   One capable of propagating several modes at a given wavelength.

8. Numerical Aperture (N.A.)
   A measure of the maximum acceptance angle for light propagation in the fiber; at angles larger than this there is no longer total internal reflection.

$$N.A. = \sin \Theta = \sqrt{n_1^2 - n_2^2}$$

where Θ = one-half of input core angle

n_1 = index of refraction of core

n_2 = index of refraction of cladding

9. <u>Step Index Fiber</u>

   One where the index of refraction is constant in the fiber and has an abrupt "step" at the surface.

APPENDIX D

TIME DIVISION MULTIPLEXING (TDM)

Reference: D.G. Fink, Electronic Engineers' Handbook, First Edition, McGraw-Hill, New York, 1975

Introduction

In TDM, message information from many channels is sampled in time sequence. The following sampling restrictions apply:

1. Each channel is sampled often enough to ensure no loss of information.

2. Frequency of sampling is fast enough for all channels to be sampled in turn in each sampling cycle.

The modulation technique most generally used is pulse code modulation (PCM). The end result is a PCM/TDM system.

Basic Calculations

1. Sampling frequency of Up Link = 1 KHz (TOW sampling rate is slightly less at 400 Hz).

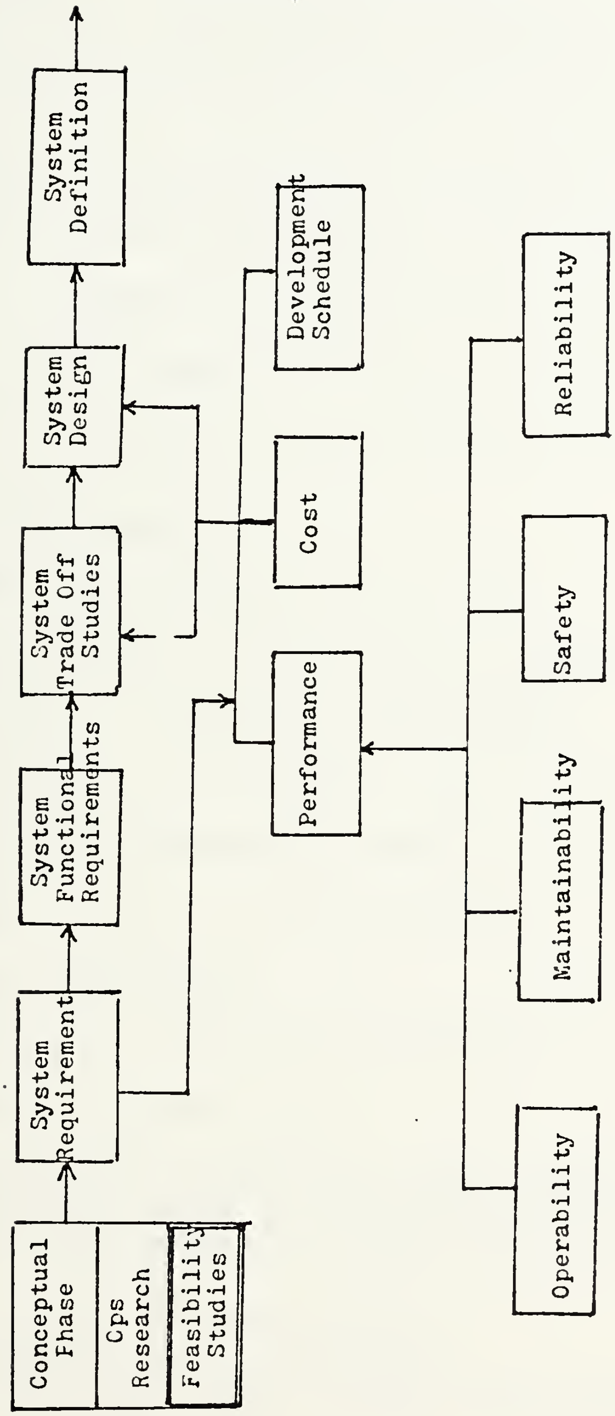
2. Four data channels into 16 bit binary PCM

3. Bits per sampling cycle = (16 x 4) + 1 = 65 bits

4. Resulting digital capacity required = 65 Kb/s.

APPENDIX E

SYSTEM ENGINEERING



SYSTEM ENGINEERING

W.P. Chase, "Management of System Engineering"
John Wiley and Sons, New York, 1974

SYSTEM ENGINEERING

1. Definition

Application of the necessary scientific and technical knowledge and skills to the study and planning of the overall system. The interrelationship of various parts of the system and the utilization of the various subsystems are fully analyzed and designed in terms of their contribution to the achievement of the specified mission and performance requirements within the given cost and delivery limitations.

2. System Requirements

a. Operational mission objectives

b. Description of conditions for deployment

c. Concept of operations and support

d. Operational performance requirements

e. System effectiveness criteria

f. Date system is to be available

g. Cost limitations

h. Development program constraints

i. Political constraints

j. Description of the technical approach which is to be validated including any "off-the-shelf" items which are to be used or to which the system is to be mated.

3. System Functional Requirements

Progressive analysis of system requirements and constraints to:

a. Formulate total system mission and functional requirements (functional flow diagram)

b. Apportion performance requirements and reliability values to subsystems

c. Describe functional design characteristics to achieve an integrated system design (functional schematic)

d. Establish criteria and standards for evaluation of system end item performance

e. Interrelate system and functional requirements with performance allocations and analyze for omissions. These will involve:

   (1) Prime mission equipment

   (2) Support equipment

   (3) Facilities

   (4) Procedures

   (5) Personnel training

   (6) Logistic support

4. <u>System Tradeoff Studies</u>

Concerned with achieving overall system operational capability by:

a. Developing a descriptive system model or alternative models to integrate inputs, outputs and system states in a real time operational environment

b. Evaluating alternatives and variations in design and selecting "best-fit" synthesis of solutions for management considerations in relation to performance cost and time requirements:

   (1) Determining how the best achievable design solution exceeds or falls short of requirements

   (2) Identifying when design and development of a system element requires achievement of new technology goals and estimating probability of success within system development constraints ("high risk areas")

   (3) Identifying problems requiring special management attention and maximum visibility for monitoring progress in development

5. System Design

Derive a coherent system design to produce a defined set of optimum outputs from given inputs with respect to time, cost and performance measures of effectiveness:

a. Alternative design approaches may be specified for deferred evaluation and final choice during system acquisition

b. Acquisition may be delayed pending development of key components

c. Design objectives or performance requirements may be compromised if the urgency to acquire some degree of the specified operational capability so dictates.

6. System Definition

System and end item performance design requirements covering:

a. Prime mission equipment

b. Support equipment

c. Facilities

d. Procedures

e. Personnel training

f. Logistics support

g. Production, test and deployment

7. Performance

Quantitative input - transformation - output characteristics to be attained in order to fulfill mission requirements under specified environmental and use conditions are employed as design goals.

8. Cost

Total costs to acquire and deploy the system to achieve the specified operational capability are developed as a cost effectiveness evaluation model. Cost categories are:

a. Development

b. Investment

c. Operation

9. Development Schedule

System milestone schedules are developed by "backing off" from the required availability date.

10. Operability

Those features and characteristics of system design which facilitate its effective use for accomplishing the operational mission objectives.

11. Maintainability

Those features and characteristics of equipment/system design and maintenance resource planning which contribute to the rapidity, economy, ease and accuracy with which the system can be kept in or restored to specified operating condition in the planned maintenance environment.

12. Safety

Those features and characteristics of equipment/system design which are intended to prevent injury to or physiological degradation of personnel.

13. Reliability

Those features and characteristics of a system that will result in it performing its required functions under the specified use conditions, without failure to complete its intended mission.

APPENDIX F

DOWN LINK (VIDEO)

Introduction

The complete design of a complex fiber optic communications system can be very detailed and complicated since the number of variables to consider are rather large. However, the basic engineering decisions to make on a user specified system center about component choices: APD, PIN, LED, ILD, fiber cable, repeaters, modulators, signal format/encoders, multiplexers and demultiplexers. The two major factors to consider are the optical power requirements and the response time requirements of the total system.

The format used for the following calculations was obtained from Ref. 9.

Basic Power Calculations

1. Required bandwidth -- 4 MHz
2. Required SNR - 7 dB [Ref. 24]
3. Terminal spacing - L = 5 Km
4. Attenuation - 3 dB/Km for fiber [Ref. 11]
   2.5 dB/Km for spools [Ref. 14]
   A = 5.5 dB/Km
5. Light source type: LED - Average output power - $P_s = 0$ dBm [Ref. 11]
6. Detector type: APD - Required received optical power - $P_r = -70$ dBm [Ref. 9]

Total power margin = $P_s - P_r = 70$ dB

7. Losses

a. Fiber loss - A x L - 27.5 dB

b. Coupling losses (assume use of pigtail fiber)

(1) NA loss - 10 log P_c/P_t = 6.6 mW/50.9 mW = 8.87 dB [Ref. 11]

where P_c = power coupled into a fiber

P_t = total source power

(2) Reflection loss - 2 x 0.2 dB - 0.4 dB

(3) Between detector and fiber - 1 dB

(4) Unintercepted Illumination (UI) loss

= 10 log A_c/A_s = 27.7 dB [Ref. 11]
less 6 dB due to fiber pigtail

where A_c = fiber core area

A_s = area of source's projected optical spot

c. Allowance for component time degradation = 1 dB [Ref. 9]

d. Allowance for temperature variations = 1 dB (assumes use of compensation circuitry)

Total loss or attenuation = 59 dBm

Excess power = 11 dB

Basic Rise Time Calculations

1. Total allowable system rise time (AST) = 0.35/bandwidth = 87.5 nsec [Ref.9]

2. Light source rise time = 19 nsec [Ref. 9]

3. Receiver module rise time = 1 nsec [Ref. 9]

4. Fiber N.A. = 0.36 n = 1.5 [Ref. 14]

5. Source: λ_o = 820 nm $\partial\lambda$ = 2 nm [Ref. 14]

6. Modal dispersion rise time = 3 nsec [Ref. 9]

7. Material dispersion rise time - 0.82 nsec [Ref. 9]

8. System Rise Time (SRT) = 21.4 nsec

Therefore AST > SRT

APPENDIX G

UP LINK (DIGITAL)

Introduction

Using the same reasoning as noted in Appendix F, the following format was used for basic calculations.

Basic Power Calculations

1. Required bit rate < 5 Mb/s

2. Required BER = 10^{-9}

3. Signal format: NRZ add -3 dBm [Ref. 9]

4. Terminal spacing $L = 5$ Km

5. Attenuation - 3 dB/Km for fiber [Ref. 11]
   2.5 dB/Km for spools [Ref. 14]
   $A = 5.5$ dB/Km

6. Light source type: ILD - Average output power -
   $P_s = 11.5$ dBm [Ref. 11]

7. Detector type: PIN - Required received optical power
   $P_r = -50$ dBm [Ref. 9]

   Total power margin $= P_s - P_r = (11.5 - 3) - (-50)$
   $= 58.5$ dB

8. Losses

   a. Fiber loss $= A \times L = 27.5$ dB

   b. Coupling losses (assumes use of pigtail fiber)

      (1) UI loss = 9 dB [Ref. 11]

      (2) NA loss = 3.5 dB [Ref. 11]

      (3) Reflection loss = 2 x 0.2 = 0.4 dB [Ref. 9]

      (4) Detector coupling - 10 dB [Ref. 9]

   c. Allowance for temperature variations = 1 dB
   (assumes use of compensation circuitry)

d. Allowance for component time degradation = 1 dB [Ref. 9]

Total loss or attenuation = 52.4 dB

Excess power = 6.1 dB

Basic Rise Time Calculations

1. Total allowable system rise time (AST) = 0.7/bit rate
   = 0.7/5
   = 140 nsec [Ref.9]

2. Light source rise time = 2 nsec [Ref. 9]

3. Photodetector rise time = 4 nsec [Ref. 9]

4. Total fiber dispersion = 3.82 nsec (Appendix F)

5. System Rise Time (SRT) = 6.53 nsec

Therefore AST > SRT

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